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Journalism

ROCKS AND ROCK MINERALS

ROCKS

AND

ROCK MINERALS

A MANUAL OF THE ELEMENTS OF PETROLOGY WITHOUT THE USE OF THE MICROSCOPE

BY

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SECOND EDITION, REVISED

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PREFACE TO THE SECOND EDITION

The First Edition of this book appeared in 1908, and as a new printing has recently become necessary it was thought desirable to bring the work up-to-date. This has now been done, without, however, altering the general character and plan of the book. The main changes that have been made are in the classification of the igneous rocks, the purpose of these changes being to bring the rock names employed more in conformity with general usage in current geologic literature. The treatment of the metamorphic rocks has been somewhat modified. Furthermore, where experience in the use of the book has indicated that the text needed expansion or clarification, changes have been freely made.

To Miss Clara Mae LeVene my thanks are due for reading the text and seeing the volume through the press.

ADOLPH KNOPF

YALE UNIVERSITY,
New Haven, Conn., Dec. 19, 1925.

PREFACE

During the last fifteen years it has been one of the writer's duties to teach the elements of Petrology to students in various branches of Engineering, Mining, Chemistry, Forestry, etc. The amount of time which these students, in their undergraduate course, can devote to the subject is limited and precludes any attempt to give them such instruction in optical-microscopical methods of research as would be worth while. The subject has to be treated from the purely megascopic standpoint, as indeed the vast majority of those who have to deal with rocks in a practical or technical way are also obliged to consider them.

In giving this instruction the author has long felt the need of a small, concise, and practical treatise in which the rocks and rock-minerals are handled entirely from this megascopic standpoint. In such works as exist either the subject matter has not been brought down to date to express our present knowledge of rocks, or it is treated largely from the microscopical or chemical standpoint, or the classifications used are based on microscopical research and are thus not available for ordinary use, or the rocks are treated incidentally with respect to some other main purpose as in works on soils, ore deposits, etc. The present work is an attempt to fill this need which the writer believes is also felt in many other institutions in which similar courses in Petrology are given. In addition to this purpose its scope has also been somewhat enlarged to meet the wants of many who have to consider rocks from the scientific or practical point of view and who are not in a position to use the microscopical method. It is hoped that it may thus prove of service to field geologists, engineers, chemists, architects, miners, etc., as a handy work of reference.

Much of the theoretical side of Petrology which has been developed during the last few years, especially in the line of petrogenesis, does not demand a knowledge of microscopical petrography for its understanding, and the endeavor has been made to present the elements of this in a simple manner. Although the author has incorporated considerable original material it goes without saying that a work of this character must of necessity be mainly one of compilation. It would be nearly impossible and in any case out of place in an elementary treatise to give by reference the thousand and one sources from which the material has been taken. It should be mentioned, however, that in the description of the minerals the writer has drawn freely upon the mineralogies of Dana, Iddings and Rosenbusch and the determinative mineralogy of Brush-Penfield. In the same way in the treatment of the rocks the petrographies of Rosenbusch and Zirkel and the geological text-book of Geikie have been freely used.

Most of the illustrations have been prepared for this work, but the wealth of material in the published reports, bulletins, etc., of the United States Geological Survey has also been freely used.

Sheffield Scientific School of Yale University.
New Haven, Conn., Jan., 1908.

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ROCKS AND ROCK MINERALS

PART I

INTRODUCTORY AND GENERAL

CHAPTER I

SCOPE OF PETROLOGY; HISTORICAL; METHODS OF STUDY

Everywhere beneath the mantle of soil and vegetation that covers the surface of the land lies rock, the solid platform upon which the superficial débris of earth rests. Here and there in mountain tops, in cliffs and ledges, we see this underlying rock projecting from the soil and exposed: we know that it must underlie the sea in the same way. The outer shell of the Earth, then, is made of rock, which forms the foundation upon which rest all the surface things with which we are acquainted. How thick this zone of rock is we do not know, but upon it we live and exert our activities; into it we penetrate for coal, oil, gas, metals, and other things upon which the material features of our modern civilization depend. It is therefore of the highest importance to us; and the information which we have acquired concerning it, by examination and study, forms a valuable branch of human knowledge.

Petrology — the Science of Rocks. Our knowledge of all the various things making up that part of the Earth which it is permitted us to examine and study has been comprehended under the heading of *Geology*. This knowledge has now increased to such a degree that the science of *Geology* has split up into a number of well-defined, subordinate branches, or geological sciences. Thus, *Meteorology* is the science of the atmosphere, the summation of our knowledge of the causes and movements of winds, storms, rain, the distribution of heat and cold, and in general the study of the various factors that affect the air and its movements and of the laws that govern them. *Physiography* takes account of the surface features of the Earth, of the distribution of land and water and of the agencies which are modifying them, the effects of climates and the various causes which together produce the topography now exhibited by the Earth's surface. *Paleontology* is the science resulting from the study of the remains of past life upon the Earth, as shown by the fossils inclosed in the rocks, and not only teaches of the different forms of life that have existed but also seeks to trace the transformation of one form into another and the various movements or migrations of life upon the Earth in past ages.

Petrology, in the same way, has now become a separate branch, one of the geologic sciences. It comprises our knowledge of the rocks forming the crust of the Earth, the results of our studies of the various component materials that form them, of the different factors that have led to their formation, and the laws governing them, and of their behavior under the action of the agencies to which they have been subjected; it also endeavors to classify the kinds into orderly arrangement.

[illegible]

The terms *Petrology* and *Petrography* are not absolute synonyms, though often so used in a general way. The former has been defined above; the latter more particularly refers to the description of rocks and especially to the study of them by means of the microscope as explained later — thus *microscopical petrography*. The term *Petrology* is used for the science in its broader aspects as well, and covers the geological and chemical relations of rocks: thus strictly defined, *Petrography* may be said to be a branch of *Petrology*. The synonym *Lithology* has become nearly obsolete. *Petrology* means the science of *rocks; Lithology,* the science of *stones,* and the word *stone* is now used in a popular way for architectural and commercial purposes or to designate any loose piece of rock of unknown origin.

Definition of a Rock. By the term "rock," geologically speaking, is meant the material composing one of the individual parts of the Earth's solid crust, which, if not exposed, everywhere underlies the superficial covering of soil, vegetation, or water which lies upon it. The popular understanding of this term, that it denotes a hard or firm substance, is not, geologically, a necessary one, for a soft bed of clay or of volcanic ash is as truly a rock as a mass of the hardest granite. Moreover, the term rock implies, within limits which will be explained elsewhere, a certain constancy of chemical and mineral composition of the mass recognized as forming a particular kind of rock. Thus the chance filling of a mineral vein by variable amounts of quartz, calcite, and ores is not accepted by petrographers as forming a definite kind of rock. The term is also used with different meanings; it may be denotive of the *substance* forming parts of the Earth's crust, as quartz and feldspar arranged in a particular manner are said to form a rock — granite — or it may refer to the masses themselves and thus possess a larger, geological significance. In a general way, the former may be said to be a *petrographic,* the latter a *geologic* usage. When the word rock is used in this broader geologic sense the mass recognized as an individual kind of rock must possess definite boundaries and show by its relations to other rock masses that it owes its existence to a definite geological process. The absolute size of the mass is not involved in this, for a seam or dike of granite cutting rocks of other kinds may be as thin as cardboard or may be a mile in thickness.

Composition of Rocks. Rocks are sometimes defined as aggregates of one or more minerals, but this is not a broad enough or wholly correct definition. Rocks may be composed entirely of minerals or entirely of glass or of a mixture of both.

Minerals are substances having definite chemical compositions and usually of crystalline structure; glasses are molten masses chilled and solidified without definite composition and structure. Rocks composed wholly of minerals may be *simple* or *compound*, that is, the rock may be formed of one kind of mineral alone, as, for example, some of the purest marbles, which consist of calcite only, or of a mixture of two or more, like ordinary granite, which is made of grains of quartz, feldspar, and mica. These subjects are treated more fully in later chapters.

History of Petrology. The science of Geology may be said to have commenced when rocks, as objects of investigation, began to be studied. As the individual minerals composing rocks or contained in their cavities were investigated by chemical means and by the goniometer, the science of Mineralogy and its related subject, Crystallography, began. At first the difference between rocks and minerals was not very clearly perceived; very fine-grained rocks composed of mineral grains so minute that they could not be distinguished by the eye or magnifying lens were thought to be homogeneous substances and similar in their nature to minerals. This continued even down to the middle of the last century.

As the knowledge of the composition and properties of minerals grew, it was seen that the coarser-grained rocks were composed of aggregates of these mineral grains, and early in the last century many common rocks had already been named in accordance with their component minerals. As investigation proceeded and geological science grew, many new combinations were discovered and the list of named rocks increased. It may be remarked here that these early geologists, armed only with a simple lens, were exceedingly keen observers and made many surprisingly correct observations on the mineral composition of quite fine-grained rocks. Various schemes of classification were proposed, some of them containing admirable features; but the extremely fine-grained rocks defied the means of investigation then at command, and in great part their composition, properties, and relations to other rocks remained unknown.

About the middle of the last century, Sorby, an English geologist, showed that by a suitable method of operation very thin slices of rocks could be prepared, and that by the study of such thin sections under the microscope the kinds of component mineral grains could be made out, their properties and relations to one another, the order in which they had been formed, the processes to which they had been subjected, and many other interesting and important features discovered. He showed that it was possible to do this even in the case of the finest-grained rocks. This method of investigation was immediately taken up, especially in Germany by Zirkel and others, and with its advent a new era in the study of rocks and the science of Petrography may be said to have begun. A flood of knowledge regarding rocks, and especially of the minerals composing them, began to rise and has kept on increasing to the present day. The study of the properties of transparent minerals under the action of polarized light received a great impulse, and the facts discovered have in turn been of immeasurable service in the investigation of rocks by this method. Thus at first attention was directed chiefly to the mineralogical side of petrology; the kinds of minerals of which rocks are composed and their properties were considered of first importance, and this is reflected in the schemes of classification devised at this period. Later, the chemical composition of rocks, both in mass and as shown in their component minerals, their origin, and the relations of the different varieties to each other began to attract more attention and have been regarded as of increasing importance down to the present day. The increasing importance of these aspects of the subject is also seen in the weight placed upon them in the more recent schemes of classification proposed for the igneous rocks, those formed by the solidification of the molten masses coming from the Earth's interior.

Classification of Rocks. According to their mode of origin and the position of the masses with respect to the Earth's crust and to each other, rocks naturally divide themselves into three main groups, which are recognized by practically all geologists. These are the *igneous* rocks, made by the solidification of molten material; the *sedimentary* or bedded rocks, formed by the deposition of sediments in water, to which may be added the small groups of æolian, or wind-formed, and ice-formed deposits; and the *metamorphic* rocks, those produced by the secondary action of certain processes upon either igneous or sedimentary rocks. In the last group the original characters are wholly or partly obscured and replaced by new ones, and these rocks are therefore most conveniently considered separately. This grouping will be used in the present work, and each group with its further subdivisions, their characters, relations, etc., will be treated by itself.

Summarizing what has just been stated, we have:

I. Igneous Rocks: solidified molten masses.
II. Sedimentary Rocks: deposited detrital material and precipitates.
III. Metamorphic Rocks: secondary — formed from I and II.

Field and Petrographic Classifications. The sedimentary rocks are classified in two ways, — in one they are subdivided according to the kinds and fineness of the mineral particles which compose them; in the other, according to the geological age in which the sediments were laid down, as shown by their position and fossils. The first is the petrographic, the second the geological, or more strictly the historical classification. In this work these rocks are treated only according to the former method. They have, so far, been simply divided according to the properties mentioned above, and as they have not yet been the subject of the detailed research which their importance demands, the simple classification adopted by geologists in the field has been followed by the petrographers.

With respect to the igneous rocks, and to a lesser degree the metamorphic ones, the case is different. The use of the microscope in the study of thin sections has shown that rocks which may appear absolutely identical, either in the field or as one simply compares hand-specimens, may be composed of entirely different minerals; or their chemical analysis may prove them to be fundamentally different in chemical composition. They may thus be quite different rocks, deserving separate names and places in any classification in which all of the essential characters of rocks are considered, and yet outwardly to the eye there may be no hint of this. There have arisen two useful terms, *megascopic* (from the Greek μέγας — great) and *microscopic,* the first descriptive of those characters of rocks which can be perceived by the eye alone or aided by a simple pocket-lens, and the second referring to those which require the use of the microscope on thin sections. It is obvious that a classification which is based upon microscopic characters as much as upon megascopic ones cannot be used in determining rocks in the field. It may be more correct and scientific, but in the nature of things it cannot be of general application and use. This subject will be treated more fully in the section devoted to the igneous rocks. It is sufficient to say here that the object of this work is to supply a field classification based upon the megascopic characters of rocks to be determined by the eye or pocket-lens, aided by a few simple means for the determination of minerals. In addition, many important facts regarding rocks, especially the igneous ones, have been discovered in these later years which are not dependent upon their classification or microscopic study, and it is intended to give some account of these in a simple general way.

Microscopical Petrography. Although this volume is not based upon the microscopical method of research, it will be of interest to indicate briefly how this is conducted and the sort of results obtained by it. To prepare the thin sections or slices of rock for study, a chip of the material as thin as can be obtained is taken. It should be, for ordinary purposes, about an inch in diameter and of firm unaltered material. It is first ground flat on a metal plate with coarse emery powder and water, and then ground very smooth on another plate with very fine powder. It is then cemented to a piece of glass by the aid of heated Canada balsam, and the other side ground down with the coarse emery until it is as thin as cardboard, or as far as it is possible to carry the operation safely with the coarse powder. It is then in a similar way ground down with the finer powder and finally finished on a glass plate with the finest flour of emery until, in the case of dark, fine-grained rocks, it becomes so thin that ordinary print may be read through it. It is next transferred, after the cementing balsam has been melted, to a microscopic object glass slide, is enveloped in balsam, and a thin cover glass is placed over it; it is then ready for use. The professionals who make a business of preparing such sections save much time in the coarser work by the use of sawing disks with diamond dust embedded in them or by using carborundum powder on disks or endless revolving wires. They become very expert in the final grinding and prepare sections the thickness of which is quite uniformly about $\frac{1}{1000}$ of an inch, experience having shown that this is best for general work. The appearance of one of these finished sections is shown in Fig. 1. By this process the minute mineral grains composing the finest-grained and blackest of basaltic lavas become transparent and may be determined under the microscope.

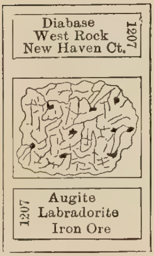
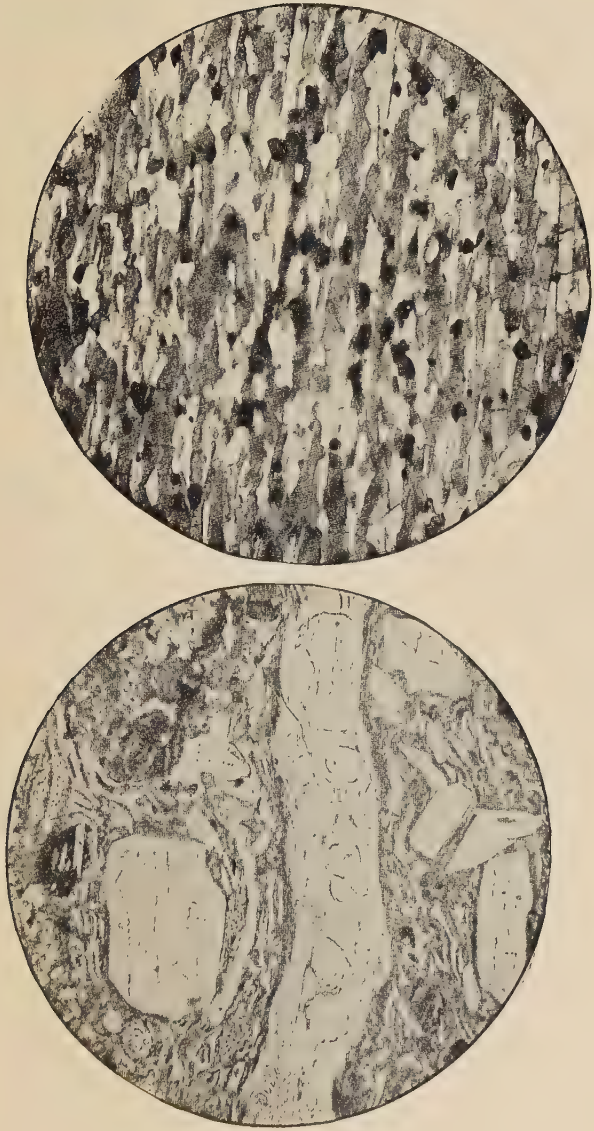


Fig. 1. Thin rock section

The microscope used in petrographic work differs from that ordinarily employed in being furnished with a variety of apparatus arranged for studying the mineral sections in polarized light. Underneath the table or stage which carries the section is a nicol prism of calcite which polarizes the light coming upward from the reflecting mirror below before it

PLATE 1.



A. Lava.

B. Schist.

THIN SECTIONS OF ROCKS AS SEEN UNDER THE MICROSCOPE.

(U. S. Geological Survey.)

passes through the section; that is, the vibrations of the ether which produce the phenomenon of light, instead of occurring in all directions, as in common light, are reduced to a definite direction in one plane.

Another nicol prism called the analyzer is fitted in the tube above the object lens so that the effects produced by the mineral particles on the polarized light, as it passes through them, can be tested and studied. The nicols can be also removed so that the effects of ordinary light can be seen. Other arrangements are provided for strongly converging the light as it passes through the minerals and for testing, in a variety of ways, the results produced.

Subjected to such processes, the transparent minerals of the rocks exhibit a great variety of phenomena by means of which the different species may be definitely determined. Crystals or fragments of crystals of an almost incredible degree of minuteness may be studied with high powers, their properties examined, and the particular variety of mineral to which they belong made out. In order to use this means of studying rocks, a good knowledge of general Mineralogy, of Crystallography, of Optics, and in particular of the optical properties of the rock-making minerals, is essential. Owing to the cost of the apparatus, the technical knowledge required in its use, and the difficulty of making thin sections, it is obvious that this method of studying rocks can never become a popular or general one, but many of the results which have been attained by it are easily understandable and may be mentioned.

Results of Microscopic Research. By the method described above, it is possible to determine the kind of mineral or mineral grains making up the most compact and fine-grained rocks; to tell whether the rock is of sedimentary or igneous origin; and, if the latter, to determine the general order in which the mineral varieties have crystallized from the molten fluid. One can see whether the crystal particles are clear and homogeneous or contain inclusions of various kinds — facts which often throw light on their origin and history; whether they are fresh and unchanged or have been decayed by the action of the elements and altered wholly or partly into other substances; whether or not they have been subjected to the enormous pressures of mountain building in the crust and are strained and crushed. It is possible to tell at once if a rock contains more or less glass associated with the mineral grains, and if it does, thus to learn with certainty its igneous origin and the fact that in all probability it is a surface lava, — glass, in the nature of things, being almost invariably confined to such rocks.

Furthermore, if the grains are not too microscopically fine it may be possible, not only to determine the kinds of minerals they are, but to measure their areas or diameters in a given section, ascertain from this the relative proportions of the different kinds of grains present, and then, when the chemical composition of the component minerals is known, compute the chemical composition of the rock mass as a whole. This factor, especially in the igneous rocks, is often of great importance in scientific classification and in other ways.

These are some of the more important features of rocks which may be discovered by their microscopic study, and they are sufficient to illustrate the value of the method in aiding geological research.*

Megascopic Study of Rocks. Although the microscope is necessary for the complete investigation of rocks, many of their important features may be observed without its use. In the coarser-grained rocks, those in which the size of the grains is one-sixteenth of an inch in diameter or more, the

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* The following works in which rock-making minerals and rocks are treated and classified according to the results of microscopical research in a more or less extensive and detailed way may be mentioned: Rock Minerals, by J. P. Iddings (John Wiley & Sons, Inc., New York). Quantitative Classification of Igneous Rocks, by Messrs. Cross, Iddings, Pirsson and Washington (Chicago University Press). Elemente der Gesteinslehre, by H. Rosenbusch (Stuttgart). Petrology for Students, by A. Harker (Cambridge University Press). Igneous Rocks, by J. P. Iddings (John Wiley & Sons, Inc., New York).

component minerals can usually be identified by the aid of the lens or by simple means. Even when much finer-grained than this, some minerals may be distinguished by certain characters that they possess, as explained in the chapter on the rock-making minerals. Even when the rocks are so fine-grained that the component grains can no longer be discriminated from each other, the color, the hardness, the style of fracture under the hammer, the specific gravity, and the behavior of fragments or of the powdered rock under the action of acids are all important characters which serve to distinguish different kinds of rocks.

Implements and Apparatus. The first requisite is a suitable hammer for obtaining material. It should be a square-faced geological hammer of the type shown in the adjoining figure. It is convenient to have one end wedge-shaped. The steel should be tempered as hard as possible without making it too brittle, otherwise the edges wear off very rapidly. If the hammer is made to order it is a great convenience to have the hole as large as possible, consistent with strength, and tapered somewhat toward the top; the handle, when thrust through the eye of the hammer, will be smaller than the outer part of the hole, and needs to be enlarged with iron wedges. This device, which is the familiar one used in securing the handles of picks, is a great convenience as it prevents the head coming off when the handle shrinks. The hammer should be

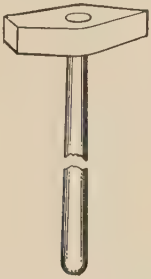

Fig. 2. Geological hammer

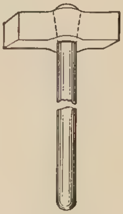

Fig. 3. Trimming hammer

of good weight, about $2\frac{1}{2}$ pounds for the head, to enable good-sized pieces of rock to be readily broken up and the fresh material within to be procured. Of course, anything in the way of a hammer or sledge may be used on occasion, but this implement will give the best service for general use.

If, in addition to procuring material for examination, it is desired to trim and shape it into specimens for the collection, a small trimming hammer will be found convenient. It should be double-headed, square-faced, and of very hard steel, and the head may weigh about 6 ounces. Hand specimens for collections are usually about 4 × 3 × 1 inches in size and are made by selecting a suitable large flake or spall obtained by the large hammer and knocking small chips from it along the edges, first on one side and then on the other, until it is trimmed to the required shape and size. A well-made specimen should show hammer marks only on the edges and none on the faces.

A pocket-lens is also essential; one of the apochromatic triplets now made by several makers of optical instruments is best, but much cheaper ones will serve the purpose. One with a focal distance of one inch, i.e., having a magnification of 10 diameters, is most convenient for general use.

In addition to the above, which are for use in the field, a small amount of the apparatus used in the laboratory for the determination of minerals will often prove of great service. This would include a blowpipe and platinum-tipped forceps for testing fusibility; pieces of quartz, calcite, and ordinary window glass for testing hardness; a simple apparatus for determining specific gravity; a magnet; a few test tubes, dilute acids, and a Bunsen gas burner or alcohol lamp for testing solubility; and a glass funnel, filter paper, and a few reagents, such as solutions of ammonia, silver nitrate, and barium chloride, for making tests by chemical reactions. A small agate or steel mortar is needed for grinding a fragment of the rock or mineral to powder for making chemical tests. This list might be increased almost indefinitely into the full equipment of a mineralogical laboratory, but most chemical laboratories contain all the apparatus and reagents necessary for the determination of minerals and rocks mentioned in this book and, where such a laboratory is not available, the material which has been named above will cover nearly all necessary demands and may be used almost anywhere.

CHAPTER II

CHEMICAL CHARACTER OF THE EARTH'S CRUST AND ITS COMPONENT MINERALS

Composition of the Earth's Interior. The origin and history of the rocks composing the solid crust of the Earth are of necessity bound up with the origin and history of the globe itself. Beyond the history that is revealed in the sedimentary rocks, however, our ideas on this subject, as regards the Earth, must, with our present knowledge, be largely of the nature of pure speculation. Below a relatively very shallow depth, the same is true with respect to the character and condition of the interior of the Earth. We do not know what it is like, and it is of course possible that we never shall. The view most generally held is that the Earth was once a molten mass, the outer shell of which solidified through cooling to a solid crust, while the interior, though excessively hot, also solidified through the enormous pressures exerted upon it by the overlying portions. Between the two is either a zone of liquid that exists as such because the pressure is not there sufficient to solidify it or a zone of heated material that will become liquid if for any cause the pressure in the crust above is diminished; this zone is regarded as the seat of volcanic and other important geological activities.

While this view has been long and is still widely held and has been of great service in explaining many geological phenomena, certain objections to it have been advanced, and recently Chamberlin has propounded another.

According to this, the Earth is regarded as never having been liquid but always a solid which has been gradually built up by the infall and accretion of relatively small solid bodies termed planetesimals. Through the enormous pressures exerted under the influence of gravity, contraction has ensued and gaseous matters have been expelled, giving rise to the atmosphere and water on the surface. This contraction is held to be the source of the interior heat, and to the issuance of the heated gases is attributed the origin of volcanic activity.

The hypotheses presented above will serve to show how widely divergent are the views in regard to this subject among scientific men at the present time and how purely speculative our ideas are.

Facts that are known. On the other hand, it must not be assumed that nothing is known of the Earth beyond that which we can see at the surface. We know, for instance, that there is a considerable increase in heat as we go downward in the crust. We know also that there are bodies of molten material, which, though they may be relatively small as compared with the size of the Earth, are yet absolutely large, and we see the upward prolongation of these molten masses to the surface in active volcanoes. We know that such molten bodies not only exist in the Earth's interior now but have also been present in past geological ages, as shown by the way in which they have been forced upward into its crust or erupted upon its surface at various stages in the Earth's history. We know that wherever the deepest-seated rocks, which underlie all the stratified and metamorphic ones, are exposed by erosion they present the general characters of igneous rocks, and thus lead us to infer that they were at one time in a state of fusion. As the sedimentary and metamorphic rocks are secondary or derived from previously existent ones, this leads to the natural assumption that they came from material originally similar to these deep-seated ones and that their substance had at some previous stage passed through a state of fusion.

Rock material, then, having been wholly or at least very largely in a molten condition, it is evidently a matter of importance that we should know something of the nature and properties of the molten fluids which have formed it. We can obtain some knowledge of them in active volcanoes where we see some of the properties of these fluids exhibited, but those properties which are most important in rock formation we can best learn by studying the igneous rocks that are the result of the direct solidification of these molten masses. This subject is, therefore, treated in the chapter upon them. There are, however, certain aspects of it which can well be considered here, and one of these is the general chemical composition of the Earth's crust.

Chemical Composition of the Earth's Crust. During recent years several thousand chemical analyses have been made of rock specimens from the visible parts of the Earth's crust. The great majority of them are from Europe and the United States, but enough have been made from other parts of the world to show, in conjunction with the microscopical studies of other specimens, that the essential facts which these analyses teach are, almost beyond question, of general application. One of the most important general truths learned through these investigations may be thus broadly stated: the general chemical composition of that part of the Earth's crust underlying the continents is everywhere similar.

The statement thus broadly made demands explanation. It does not mean that one portion of the rock crust is composed of exactly the same chemical elements in exactly the same proportions as any other portion. It means that it is composed of the same elements and that, although these may vary greatly in proportions from place to place or from one kind of rock mass to another, if we take large areas involving many kinds of rocks the average of such areas will be very nearly alike. Thus the composition of the average rock computed from all the analyses made of specimens from the United States is essentially the same as the average computed from the analyses of the rocks of Europe. The average rock of New England is essentially that of the Rocky Mountains region. On the other hand, a large part of the Province of Quebec is composed of one kind of rock which extends with monotonous sameness over a vast area; the composition of this is not the same as that of the average rock, and if we were considering this particular part of the continent we should have to increase our area greatly to obtain a correct average. Some parts of the continental areas are covered with limestone, which is essentially carbonate of calcium alone, but is a relatively thin, concentrated coating of a special substance. We should have to balance it with large masses of other rocks.

The average rock of the Earth's crust has been computed from the analyses by Clarke and by Washington, and the results are shown in the table below in Column A.

	A 93 Per Cent Lithosphere	B 7 Per Cent The Ocean	C Average with Atmosphere
Oxygen	46.71	85.79	49.52
Silicon	27.69	......	25.75
Aluminum	8.07	......	7.51
Iron	5.05	......	4.70
Calcium	3.65	0.05	3.39
Magnesium	2.08	0.14	1.94
Sodium	2.75	1.14	2.64
Potassium	2.58	0.04	2.40
Hydrogen	0.14	10.67	0.88
Titanium	0.62	......	0.58
Carbon	0.09	0.002	0.09
Chlorine	0.04	2.07	0.19
Phosphorus	0.13	......	0.12
Sulphur	0.05	0.09	0.05
All others	0.35	0.008	0.24
	100.00	100.000	100.00

Clarke has also calculated that if we assume that the crust has this composition to a depth of ten miles and add the water of the oceans and the gases of the atmosphere, the general average of the whole will be that shown in Column C of the above table. Even if these results are not very accurate they must be approximately so, and they are of value in showing the relative proportions of the elements in the outer part of the Earth. Recent investigations tend to show that the deeper portions of the crust, such as are revealed in the areas of Pre-Cambrian rocks, approximate the composition of a granodiorite or granite carrying 68 per cent of SiO_2. Finland is the only large area that has so far been accurately sampled.

The Elements of Geological Importance. From the table just given we see that the first eight elements are present in quantity, and are, therefore, of geologic importance. Oxygen forms about one-half of the outer part of the Earth, and the quantity in the atmosphere and in the ocean is small, compared with that locked up in the underlying rock. Silicon comes next, forming about one-fourth, and after it are aluminum and five other metals, of which iron is the most important, the others being calcium, sodium, potassium, and magnesium, in the order of their importance. After these comes a small group of four elements, which, although of secondary rank in quantity, demand mention: they are, hydrogen, titanium, carbon, and chlorine. Of these, titanium is a rather inert element from the geological standpoint, plays no important part in geological processes or results, and may, therefore, be dismissed. The hydrogen and carbon, on the contrary, are of much importance; they are of great activity in geological processes, produce results of petrologic interest, and must therefore be considered with the primary group first mentioned. All the other elements, however important in special cases, or for organic life or civilized activities, are from the standpoint of general geology and petrology of relatively little interest.

Combinations of Chemical Elements. Except oxygen, carbon, and possibly to an unimportant extent iron, the elements mentioned above do not occur alone, or native; they are always combined in some form, producing compounds known as minerals. We may state this chemically by saying that they are either in combination with oxygen as oxides or are in combination as salts. Two, carbon and silicon, are negative elements — their oxides, CO_2 and SiO_2, are anhydrides of acids; the others, leaving hydrogen aside, are metals, or positive elements whose oxides act as bases. The oxide of aluminum,

Al_2O_3, acts sometimes as a base and sometimes as a weak acid, especially in combination with strong bases, such as soda, Na_2O, and potassa, K_2O, and in combination with silica, SiO_2. Fe_2O_3 acts as an acid in spinels.

From what has been said, it is apparent that we have to deal with the following oxides, which are of chief petrologic importance.

ACIDIC OXIDES

SiO_2, silica, in combination and free as a solid.
CO_2, carbon dioxide, in combination and free as a gas.

BASIC OXIDES

Al_2O_3, alumina, in combination and free solid, sometimes acidic.
Fe_2O_3, ferric oxide, in combination and free solid.
FeO, ferrous oxide, only in combination in solids.
MgO, magnesia, in combination and free, solid.*
CaO, lime, only in combination in solids.
Na_2O, soda, only in combination in solids.
K_2O, potassa, only in combination in solids.

The above table is given in order of decreasing acidity and increasing basicity from top to bottom. To this list we should also add water, H_2O, which occurs free in the gaseous, solid, and liquid states, and in combination.

Since we are considering rocks, it is evident that of these oxides and their combinations we need to regard only those which form solids. These are the compounds of silicic and carbonic acid, or silicates and carbonates, and the oxides of silicon, aluminum, and iron.

Ice, the solid form of water, may also be regarded as a rock, but as such needs no further consideration in this work. Combinations of the oxides of aluminum, iron, and magnesium and of the silicates with water also occur. Combinations with sulphur as sulphides and sulphates, with phosphorus as phosphates, and with chlorine as chlorides are at times of local importance though never having the general interest of those mentioned above. They receive attention in their appropriate places.

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* The solid MgO occurs as the mineral periclase, excessively rare.

PART II

ROCK MINERALS

CHAPTER III

IMPORTANT PROPERTIES OF MINERALS

Since all rocks, with the exception of a few glassy ones of igneous origin, are composed of minerals, it is of first importance in their study and determination that a good knowledge of the important rock-making minerals, with their obvious characters and properties, should be had. This is so indispensable that Part II of this book is devoted to rock minerals, the study of the rocks themselves being deferred. Part II, therefore, contains: first, a general account of those properties of minerals which are of value in megascopic determination; second, in a succeeding chapter, a description of the minerals individually; and third, methods for their determination.

Minerals Defined. A mineral is defined as any inorganic substance that occurs in nature and has a definite chemical composition. To this, for petrographic purposes, we should add that a mineral is a solid and usually has a definite crystalline structure. The word mineral is commonly used in two ways with different meanings: in one, which may be termed the abstract chemical sense, we refer to a compound having a certain composition, as in speaking of calcite we mean the compound $CaCO_3$, carbonate of calcium; in the other usage we speak of the minerals of a rock and mean thereby the actual crystal grains, as distinct entities that compose the rock.

Crystals Defined. Most chemical compounds, when their atoms are free to arrange themselves in space and the conditions are proper for them to assume solid form, as for example when they solidify from solutions, appear in *crystals*. That is, the atoms arrange themselves in a definite geometric system, characteristic of that compound, and governed by mathematical laws, which give the solid a definite internal structure and an outward form bounded by planes which are always placed at certain angles to one another. Thus minerals crystallize in cubes, octahedrons, prisms, etc. The conditions prevailing during the forming of a rock are sometimes such that a mineral can assume outward crystal form, and it is then bounded by distinct planes; more commonly, however, the growing crystals interfere with one another and have no distinct form, or, as in the sedimentary rocks, they are only fragments of former crystals, or their plane surfaces have been worn off by attrition. Such grains are sometimes called *anhedrons* (from the Greek, meaning, without planes).

List of Properties. The chief properties of the rock-making minerals by which they may be known are their *crystal form*, *color*, *cleavage*, and *associations;* these are perceived by the eye, and in addition we have their *hardness*, *specific gravity*, and their behavior *before the blowpipe* and with *chemical reagents*, properties which demand some form of testing with apparatus.

Crystal Form. The mineral grains which compose rocks do not, as a rule, possess good outward crystal form, as mentioned in a preceding paragraph. The reason for this is that, in the igneous and metamorphic rocks, the growing minerals interfere with one another's development, and thus, while they may roughly approximate to a certain general shape which the mineral has endeavored to assume, the outer surface is not composed of smooth definite planes; while in the sedimentary rocks the grains are either broken fragments or have been rounded by rolling and grinding. It may happen, however, when crystallization begins in a liquid molten mass that one or more kinds of minerals commence growing in crystals scattered through the mass and complete their period of growth before the other minerals that are present have commenced to crystallize. Here the crystals have not been interfered with, and they may exhibit good outward crystal forms, bounded, therefore, by distinct planes. This feature is well shown in those kinds of igneous rocks that are described elsewhere as *porphyries*. Likewise in the metamorphic rocks, certain minerals commonly appear in such well-bounded, distinct crystals as to indicate that the conditions were such as to permit them to develop their own characteristic crystal boundaries during their period of growth. Striking examples are the excellent crystals of garnet, often seen in the rock known as *mica schist*.

In general, the distinctive outward crystal form or shape of minerals in rocks is wanting and cannot be used as a means for determining them, but in many special cases it may be well developed in rock-making minerals and it can then be very useful. The shapes in which each mineral is most likely to occur are described under the heading of that mineral in the descriptive part of this book.

Color. The color of minerals, when used with proper precautions, is also a very useful property for helping to distinguish them. This color is dependent upon their chemical composition, in which case it may be said to be *inherent*, or it may be due to some foreign substance distributed through them and acting as a pigment, and may then be termed *exotic*. It is because the color of the mineral grains of rocks is frequently exotic that precaution must be used in employing it as a means of discrimination.

In regard to *inherent* colors, neither silica nor carbonic acid in combination as silicates and carbonates has any power of producing color, and so far as they are concerned, such compounds would be colorless, or, as will be presently explained, white. So, silica alone, as quartz, is naturally colorless. The same is also true of the metallic oxides, alumina, lime, and magnesia, and of the alkalies, soda and potash. Thus, carbonate of calcium, or calcite, carbonate of calcium and magnesium, or dolomite, oxide of aluminum, or corundum, silicates of calcium and magnesium, silicates of aluminum and the alkalies, or feldspars, are all inherently colorless minerals. The metallic oxides that chiefly influence the color of rock minerals are those of iron, chromium, and manganese, and the only one of these that is of wide petrographic importance is iron, especially iron as ferric oxide. The minerals containing iron as a prominent component are dark green, dark brown, or black, and these colors may ordinarily be regarded as indicative of this metal.

The *exotic* colors which minerals frequently exhibit may be due to one of two causes. It may happen that a minute amount of some compound of an intensely colorative character is present in chemical combination. Thus a minute amount of manganese oxide in quartz is supposed to produce the amethyst color, traces of chromic oxide sometimes color silicates green, and probably copper does also. Or the color may be due to a vast number of minute bodies dispersed through the crystal as inclusions. These minute specks may have a distinct color of their own and thus act as a pigment, as when, for example, quartz is colored dark red by a reddish dust of ferric oxide particles in it; or the inclusions may be so arranged in regular systems as to act refractively upon light, breaking it up and producing a play of prismatic colors, or opalescence, in the substance. Usually in the latter case, one color predominates and gives its character to the mineral. A good example of this is seen in the variety of feldspar called labradorite, a constituent of the rocks called *anorthosite* and *gabbro*, which often shows a fine play of colors, a rich dark blue usually being predominant.

The *white color* which so many rock-making minerals exhibit may be due to minute inclusions, as when feldspars are sometimes, through alteration, filled with scales of kaolin or white mica; but more commonly it is due to the reflection of light from the surfaces of innumerable microscopic cracks and crevices which everywhere permeate the mineral substance. Such minerals are really colorless and transparent. The effect is the same as if a piece of colorless glass should be ground to powder, which would of course be white. Hence, white minerals are not regarded as possessing any color. They are often free from cracks and are then colorless and transparent. Good examples of this are such common minerals as quartz, calcite, and feldspars. As explained in the discussion of cleavage, these cracks in feldspar are sometimes so regularly arranged as to produce a play of colors, giving the mineral an opalescence or pearly luster with a distinctly predominating color tone like that mentioned above as produced by inclusions.

Streak. In the determination of minerals we may be guided not only by the color that they show in the solid form, but also by the color that the mineral substance presents when reduced to powder. The powder may be obtained by grinding a small fragment in a mortar, but it is more easily produced by scratching a sharp point of the mineral across a plate of unglazed porcelain; the color of the resultant streak is, of course, that of the powdered mineral. While any piece of unglazed porcelain will answer fairly well, small plates are specially made for this purpose and sold by dealers in chemical apparatus.

The color shown by minerals in the powdered state is usually much lighter than that which they exhibit in the mass, and sometimes very different. It is most useful in helping to discriminate the dark-colored minerals, especially the metallic oxides and sulphides of the heavy metals used as ores, and hence its application with the light-colored silicates and carbonates which chiefly form the rock-making minerals is much more limited and of lesser value. In these minerals it is sometimes useful in distinguishing exotic colors from natural ones; for the color of the streak is generally that of the mineral substance itself, and the pigment or other impurities which produce an exotic color must be present in very large amount to exert a definite influence. Thus calcite is colorless or white, but some varieties are yellow, brown, or red. The streak of all of them is white or barely tinted, except in unusual instances. The feldspars are normally white or colorless, but in some rocks, such as *anorthosite*, they may be black and at first glance might be mistaken for an iron-bearing mineral; the streak, however, is white and helps to show their true character.

In the field, the bruised surface of the rock, where struck by the hammer, often shows the powdered minerals, giving in a rough manner the color of the streak; or a bit of the substance may be ground between two hammer surfaces and the powder rubbed on white paper.

Cleavage. When mineral bodies possess crystalline structure, it frequently happens that the arrangement of the physical molecules composing them is such that the force of cohesion is less in some particular direction or directions than in others. Along such directions, if suitable means be employed, such as placing the edge of a knife upon the mineral and striking with a hammer, the body will tend to split or cleave. The degree of perfection in which minerals possess this property is very variable; some, like mica, which is used for stove windows and lamp chimneys, are capable of being almost indefinitely split into thin leaves; others, like the feldspars, have a good cleavage; while some, like quartz, have no apparent cleavage. When the cleavage is very good the new surfaces are smooth and shining like the original surfaces of a crystal, and the cleavage is termed *perfect.* This property, being then so distinctive, is a most useful one in helping to determine minerals, especially in rocks in which the mineral grains on the surface, when broken by the hammer, everywhere show shining cleavage faces. It must not be imagined that the directions of cleavage occur at random in a mineral; on the contrary, they always bear a definite relation to the special crystal form that characterizes a particular mineral. If the latter has two directions in which it may be cleaved, like feldspar, for example, the angle between the two surfaces is, for a feldspar of a certain definite chemical composition, always the same. Some minerals, like mica, have only one direction in which there is good cleavage. Others have two directions; sometimes the two are exactly alike in ease of splitting, and sometimes unlike, one being better than the other. Again, there may be three directions in which cleavage can be produced, all alike as in calcite, or unlike as in barite (heavy spar, $BaSO_4$); or there may even be four or more. Whether the cleavages are alike or unlike, when there is more than one, depends not only on their direction in the crystal, but also on the geometric form or system in which the mineral has crystallized. A description of these relations would involve too much of the principles of crystallography for discussion in this place, but the following will be helpful in understanding certain terms frequently used.

A. Good cleavage in one direction only: the mineral grains in the rock in this case tend to be developed in tables, folia, or scales, the surface of which is parallel to the cleavage. This tendency is well shown in such minerals as the micas and chlorite.

B. Good cleavage in two directions and both alike in ease of splitting: the minerals are likely to occur in elongated forms parallel to the cleavage, which is spoken of as being *prismatic*. Elongated forms determined by prismatic cleavage are shown by the minerals hornblende and pyroxene. If the two cleavages are not exactly alike, the mineral still is often elongated in the direction of the edge produced by the meeting of the two cleavage planes. It may be sometimes columnar and sometimes tabular, parallel to the better cleavage. The feldspars, which form the free-developed crystals in porphyry, often show such tabular or columnar forms.

C. Good cleavage in three directions and all alike in ease of splitting: if the three planes are at right angles to each other the mineral will break up into cubes and the cleavage is *cubic* or apparently so; if they are at some other angle, rhombs will be produced and the cleavage is called *rhombohedral*. Cubic cleavage is well shown by galena, PbS, the common ore of lead, and by rock salt; it is not exhibited by any common rock-making mineral. Rhombohedral cleavage is characteristic of the common rock-making carbonates, calcite, $CaCO_3$, and dolomite, $CaMg(CO_3)_2$. Three unlike directions have the same practical effect as two unlike, and four directions are not of importance in megascopic petrography, as no common rock-making mineral exhibits them.

If a rock with component mineral grains sufficiently coarse to be readily studied by the pocket-lens — the size of peas, for example — be carefully examined, it will be found that almost without exception, where a mineral shows a cleavage face, it will be full of minute cracks and fissures. These cracks are parallel sometimes to one cleavage and sometimes to all the cleavage directions the mineral has. In addition to the cleavage cracks there are also irregular lines of fracture which do not correspond to any definite direction. Commonly, the mineral grains of rocks not only contain these large cleavage cracks and irregular fractures which can be perceived with the eye or with the aid of the lens, but, in addition, they are everywhere rifted by similar ones so minute that they can only be detected in thin sections of rocks under high powers of the microscope. It is the reflection of light from these minute microscopic cracks that renders so many minerals opaque and white that would otherwise be colorless and transparent. These cracks and fissures have been produced by the various forces to which the rocks have been subjected; sometimes they are due to the contraction following a heated stage as in metamorphic and igneous rocks, and sometimes and more generally to the intense pressures and strains to which the rocks of the Earth's crust are and have been subjected. Minute as the rifts in the mineral grains are, they are of great importance in geologic processes, for by means of them, and drawn by capillary action with great force, water containing CO_2 in solution penetrates not only the rocks but even the interior of the individual grains, and alters and changes them into other minerals and the rocks into soil.

Fracture. The appearance of the surface obtained by breaking a mineral in a direction other than that of cleavage, or a mineral that does not possess cleavage, is called the *fracture* of the mineral. If the mineral is fibrous in structure, the fracture may be *fibrous;* or it may be rough and uneven, or *hackly;* if the mineral is fine-grained and homogeneous it will be *conchoidal,* that is, it will present a sort of shell-like appearance such as is shown on surfaces of broken glass, which recall the inside or outside of a clam shell. Rocks that are extremely fine-grained and homogeneous, like some flints and glassy or fine-grained compact lavas,

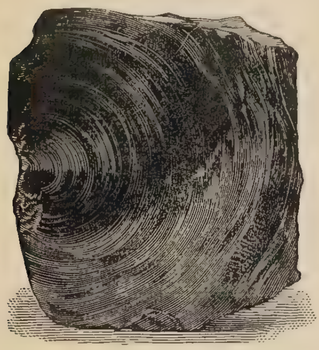

Fig. 4. Conchoidal fracture in obsidian volcanic glass

also have a conchoidal fracture that is more or less pronounced. Quartz is the most common mineral that gives a good example of conchoidal fracture.

Associations of Minerals. The facts that certain kinds of minerals are likely to be found together in the same kind of rock and that the presence of certain minerals excludes the presence of certain others are of great value in petrography, but are of much greater use in microscopic work, where the distinguishing characters of minerals are easily made out, than in field determinations. Even in megascopic petrography, however, these facts are at times of practical use; thus the fact that the two minerals, quartz and nephelite, cannot occur naturally together as rock-making components is of value in discriminating between certain rocks. The various relationships of this kind that are of importance will be mentioned in their appropriate places.

Hardness. This property is of great value in helping to make determinations of minerals, and it is likewise very useful in the field in making rough tests of rocks. The hardness of minerals is determined by comparing them with the following scale:

Scale of Hardness

1. Talc.
2. Gypsum.
3. Calcite.
4. Fluorite.
5. Apatite.
6. Feldspar.
7. Quartz.
8. Topaz.
9. Corundum.
10. Diamond.

This means that each mineral, if used in the form of a sharp point, will scratch smooth surfaces of all the minerals preceding it in the list but of none succeeding it. If, for example, a fragment of an unknown mineral is found to scratch calcite, its hardness is greater than 3; if it will not scratch fluorite, but, on the contrary, is scratched by it, its hardness is not so great as 4, but must be between 3 and 4, or approximately $3\frac{1}{2}$.

The point of a pocket-knife blade as ordinarily tempered with a hardness of a little over 5, and pieces of common window glass with hardness of about $5\frac{1}{2}$ are very useful for testing the hardness of common minerals and of the rocks made up of them. A common brass pin point is a little over 3 and will scratch calcite; the finger nail is a little over 2 and will scratch gypsum.

Specific Gravity. The specific gravity of a substance is its density compared with water or the number of times heavier a given volume of the substance is than an equal volume of water. It is obtained by weighing a piece of the mineral or rock in air and then in water; the difference between the two is equal to the weight of an equal volume of water (the volume displaced) and we have

$$\frac{\text{wt. in air}}{\text{wt. in air} - \text{wt. in water}} = \text{Sp. Gr.}$$

The operation may be carried out with one of the special forms of apparatus devised for determining specific gravity and described in the manuals of determinative mineralogy, or it may be done with a chemical, an assay, or a jeweler's balance. The specimen is first weighed in the pan and then suspended from it by a hair and weighed in water. A piece about one-half inch in diameter is convenient both for minerals and rocks, but with minerals it is frequently necessary to select a fragment smaller than this in order to obtain pure homogeneous material, without which, it is perhaps needless to say, the determination is of little value. Adherent air bubbles and air in cracks are best gotten rid of by boiling the fragment in water and then allowing it to cool before weighing. If the mineral has an invariable chemical composition and crystal form, as for example, quartz (SiO_2), calcite ($CaCO_3$), etc., the specific gravity is an invariable quantity, and departures from it must be due to the presence of impurities. Many minerals, however, while they retain the same crystal form, vary considerably in chemical composition in that one metallic oxide may be more or less replaced by another similar oxide or oxides. Thus we find minerals which at one end of a series contain magnesia, MgO, and at the other end ferrous oxide, FeO, and between these extremes all degrees of mixtures of these two oxides. In accordance with such variations the specific gravity of the mineral varies. The pyroxenes, amphiboles, garnets, olivines, etc., are examples of this, and it accounts for most of the variations in specific gravity which may be observed in the annexed table.

SPECIFIC GRAVITIES OF ROCK MINERALS

Arranged in Descending Order

5.2	Magnetite	2.86	Muscovite
5.2	Hematite	2.85	Dolomite
4.9–5.1	Pyrite	2.80	Talc
4.7–5.1	Ilmenite	2.75	Anorthite
3.95–4.1	Corundum	2.73	Labradorite
3.6–4.0	Limonite	2.72	Calcite
3.5–4.2	Garnet	2.65–2.75	Chlorite
3.75	Staurolite	2.65	Quartz
3.5	Topaz	2.62	Albite
3.56–3.66	Cyanite	2.6	Kaolin
3.4	Vesuvianite	2.5–2.65	Serpentine
3.2–3.5	Pyroxene	2.57	Orthoclase
3.27–3.37	Olivine	2.55–2.65	Nephelite
3.25–3.45	Epidote	2.45–2.50	Leucite
3.0–3.4	Amphibole	2.32	Gypsum
3.16–3.2	Andalusite	2.27	Analcite
3.1–3.2	Chondrodite	2.25	Natrolite
3.15	Apatite	2.15–2.30	Sodalite
3.0–3.15	Tourmaline	2.15–2.2	Heulandite
2.95	Anhydrite	2.1–2.2	Stilbite
2.8–3.1	Biotite	2.1–2.2	Opal

Blowpipe Reactions. The rock-making minerals, which are chiefly carbonates and silicates, do not as a rule exhibit before the blowpipe very characteristic reactions by which they may be readily determined, as do so many of the ores, the oxides and sulphides of the heavy metals. Still, the relative degree of *fusibility* shown by thin splinters, the *coloration of the flame,* and the characters of the *bead* which may result from fusing the mineral with a flux are properties which may be of great service in helping to determine these minerals, and in so far as they have value in this direction they are mentioned in the description of the minerals. If instruction in the use of the blowpipe is desired it should be sought in one of the manuals devoted to that purpose.

Chemical Reactions with Reagents. Certain qualitative chemical tests which can generally be made with a few reagents and simple apparatus are of great service in mineral determination and in aiding to classify rocks. In Chapter V, in which the methods for the identification of minerals are given, these tests and the proper ways of making them are fully described.

CHAPTER IV

THE ROCK-MAKING MINERALS

SEC. 1. *Primary Anhydrous Silicates and Oxides*

These minerals, from the geological standpoint, are the most important in forming rocks. They are the most abundant and the most widely diffused. They are the chief minerals that are formed by the cooling and crystallization of the molten fluids of the Earth's interior, and hence they are the main components of the igneous rocks. The greater part of the metamorphic rocks are also made up of them, and in the sedimentary beds they are important constituents.

It is difficult to draw a sharp line between the absolutely anhydrous minerals and those containing considerable quantities of combined water. Thus, most hornblendes, micas, and epidotes contain small amounts of hydroxyl and yet are ordinarily considered as anhydrous, compared, for instance, with kaolin, serpentine, and chlorite. In the same way feldspar, hornblende, and pyroxene are thought of as primary minerals although we know that in some cases they are of secondary origin, that is, they have been formed at the expense of previously existent minerals. The grouping as given is largely a matter of convenience; it includes minerals that are always anhydrous and always primary and that thus give a certain distinctive character to the group, but it also includes many minerals that are at times secondary and some that are hydrous, because on account of their mineralogic positions and affinities it is more convenient and natural to consider these minerals in this connection.

In the following section, only such silicates and oxides are treated as are both hydrous and secondary.

a. Silicates

The silicates are salts of various silicic acids, in which the hydrogen atoms have been replaced by various metals or radicals composed of metals in combination with oxygen, hydroxyl, fluorine, etc. The three important silicic acids which in this group form rock minerals are *polysilicic acid*, $H_4Si_3O_8$, *metasilicic acid*, H_2SiO_3, and *orthosilicic acid*, H_4SiO_4. The silicates treated as of importance on account of the functions which they have as rock-making minerals include the feldspar, feldspathoid, mica, pyroxene, amphibole, olivine, garnet, tourmaline, and epidote groups, and a few other less common ones.

Feldspars

The term feldspar is not the name of a single mineral of a definite chemical composition like quartz, SiO_2, but is the designation of a group of minerals which have a general similarity in chemical and physical properties. They are indeed so much alike in general characters and appearance that in determining rocks by megascopic features they cannot be told apart except in special cases, and it is, therefore, best to treat them as a group, and at the same time mention those characters by which, when possible, they may be distinguished.

The rock-making feldspars include three kinds and their solid solutions as follows:

a. *Orthoclase*, $KAlSi_3O_8$, silicate of potassium and aluminum;
b. *Albite*, $NaAlSi_3O_8$, silicate of sodium and aluminum;
c. *Anorthite*, $CaAl_2Si_2O_8$, silicate of calcium and aluminum;
Alkalic feldspar, $(K,Na)AlSi_3O_8$, solid solutions of *a* and *b*;
Plagioclase feldspar, $(NaAlSi_3O_8)_x + (CaAl_2Si_2O_8)_y$, solid solutions of *b* and *c*.

The simple feldspars are mostly confined to the crystals found in veins, druses, etc.; they sometimes occur as the component grains of rocks, but are comparatively rare; in the great majority of cases the feldspars are either mixtures of orthoclase and albite in varying proportions, but usually with a considerable excess of the potassium compound, and are then called *alkalic* feldspar, or they are solid solutions of albite and anorthite and are then known as soda-lime feldspars or *plagioclase.* A complete gradation from pure albite to pure anorthite occurs, and the series has been divided into groups according to the different proportions of the albite and anorthite molecules; one of the most important of these groups is *labradorite,* in which there are about equal amounts of the two.

Mixtures of *a* and *c*, of the potassium and calcic feldspars, have been found to occur but are so rare that for practical purposes they may be neglected.

Form. Orthoclase is monoclinic in symmetry, and when in distinct well-made crystals, it commonly takes the forms shown in the accompanying figures. Sometimes the crystals are stout and thick in their habit or appearance as in Fig. 5, sometimes they are thin and tabular parallel to the face *b* as in Fig. 6, and again they may be rather long and columnar as in Fig. 7. In orthoclase the face *c* is always at right angles to the face *b*. In albite and anorthite, the crystallization of which is triclinic, these faces *c* and *b* are not at right angles but are slightly oblique; this is also true for all of their mixtures or the plagioclase group in general. Some mixtures of orthoclase and albite, as well as certain varieties of the pure potassium compound $KAlSi_3O_8$, called *microcline,* are also slightly

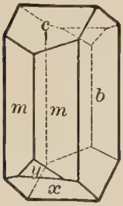

Fig. 5

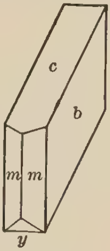

Fig. 6

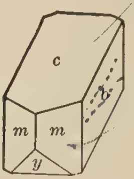

Fig. 7

Basal surface.

Prism faces.

oblique, but in all the instances mentioned the amount of departure from a right angle is only a few degrees and, even under favorable conditions, can scarcely be perceived by the eye and must be measured by a goniometer to be appreciated. It cannot, therefore, under ordinary circumstances, be used as a means of discrimination between the alkalic and plagioclase feldspars. The forms of the crystals in which the plagioclase feldspars appear in rocks when they have the opportunity to crystallize freely are similar to those above shown for orthoclase in Figs. 5–7.

It is only in the phenocrysts of porphyritic igneous rocks and in the miarolitic druses of the granular igneous ones that these minerals have an opportunity to assume the free crystal forms described; in ordinary cases their crystallization is interfered with by the growth of other minerals or of other crystals of feldspar, and they are thus seen in shapeless masses or grains. Nevertheless, feldspars have a tendency to assume these free crystal forms, and in some rocks, such, for instance, as the syenites, which are mainly composed of feldspar, may have more or less perfectly the shape of flat tables or of rude laths, according as they approximate to Fig. 6 or Fig. 7.

Twinning. Crystals frequently appear compound, as if built of two halves, one of which had been revolved 180° around an axis, perpendicular, as a rule, to the plane of junction along which the two parts have grown together. Such an arrangement is called a twin crystal. Feldspars very commonly occur in twin crystals, one of the most frequent arrangements being that illustrated in Fig. 8 and known as the *Carlsbad* twinning, from the town of that name in Bohemia where excellent examples have been found. It is as if a crystal like that shown in Fig. 5 were cut through parallel to the face *b*, one of the parts revolved 180° around a vertical axis parallel to the edge *mb*, and the two parts pushed together so that they mutually penetrate. In Fig. 9 the same arrangement is seen as it appears to an observer looking down on the face *b* of the crystal; *acya* is the outline of the original crystal; if this is cut out in a piece of paper and then turned over 180° or upside down and laid on *acya* so that the edges *aa* are brought together, it will give the result seen in the figure. In the twin crystal illustrated in Fig. 8 the face *c* slopes toward the observer, the face *y* slopes away behind; in the twinned half this is reversed. As explained under the cleavage of feldspars, this fact is of importance in helping to recognize these twins when the outward crystal form is imperfect or wanting. Carlsbad twins of the character described are found in all the different varieties of feldspar; they are most perfectly developed in the phenocrysts of the porphyritic igneous rocks, especially in the large orthoclase phenocrysts of some granite porphyries.

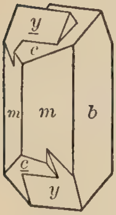

Fig. 8

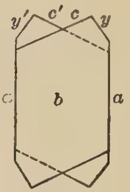

Fig. 9

In the Carlsbad twin the plane of junction of the two parts is one parallel to the face *b*; the axis on which one part is revolved is the vertical line parallel to the edge *ab* of Fig. 10 and not one perpendicular to *b* or parallel to the edge *ac*, which is usually the case in twinning, as already mentioned. The face *c* in orthoclase makes a right angle with *b*; the outline of the face *a* is, therefore, a rectangle, and if the crystal were divided along the dotted line by a plane parallel to *b* and one of the halves revolved 180° on an axis parallel to the edge *ac*, that is, perpendicular to *b*, it would appear precisely as before and no twinning would occur. The crystallographic reason for this is that *b* is a symmetry plane, since the crystal is monoclinic, and a symmetry plane cannot be a twinning plane.

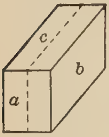

Fig. 10

In the plagioclase group, in albite, anorthite and their admixtures, the face *c* makes an oblique angle with the face *b*; the face *a* is, therefore, a rhomboid and not a rectangle as shown in Fig. 11. If this crystal is divided along the dotted line and one of the halves revolved 180° it will present the appearance seen in Fig. 12; the face *c* and the lower *c*, now brought on top, slope toward each other, forming a re-entrant angle, while below they produce a salient angle. A twin crystal is, therefore, produced, and this kind of twinning is known as the *albite* method because it is so generally found in that variety of feldspar. A complete crystal of this kind is seen in Fig. 13. The crystallographic reason why this can occur is because these feldspars are triclinic; they have, therefore, no symmetry plane, and any one of the faces might serve as a twinning plane.

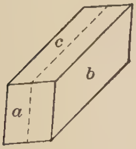

Fig. 11

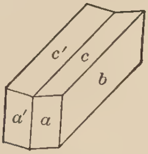

Fig. 12

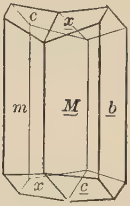

Fig. 13

lysynthetic **Multiple Twinning.** In nature, in actual practice, we rarely find a single albite twin of the kind described above. In the rock-making plagioclases the crystals are divided again and again into thin slices, and these are alternately twinned upon one another, producing the effect seen in Fig. 14. Indeed, this albite twinning descends to such a remarkable degree of fineness that the twin layers are less than the one-hundred-thousandth of an inch in thickness and are scarcely to be per-

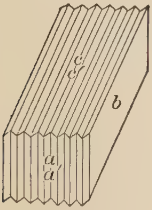

Fig. 14

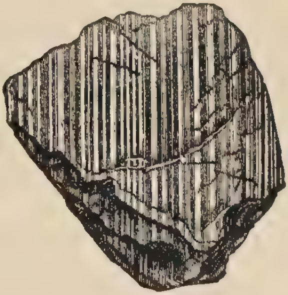

Fig. 15

ceived in thin sections in polarized light under the highest powers of the microscope. It frequently happens, however, especially in those feldspars containing much lime, like labradorite, that the twinning is coarse enough to be readily seen by the naked eye; one cleavage surface of such a feldspar appears as if ruled by fine parallel lines or striations, as illustrated in Fig. 15. Even when very fine and on a small cleavage surface of a feldspar grain embedded in the rock, this multiple twinning may be distinctly seen by a proper adjustment of the light reflected from the surface and the use of a good lens.

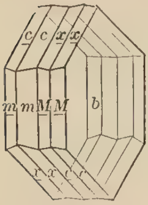

Fig. 16

Sometimes feldspars are twinned according to both the Carlsbad and the albite laws; they may be seen divided into the Carlsbad halves by the reflection of light from the cleavage, and each of these ruled by the fine lines of albite twinning. An illustration of the combination of these two, each Carlsbad half divided into albite halves, is seen in Fig. 16. The practical use of the twinning of feldspars is explained in the paragraph on methods for their determination. Other methods of twinning besides those mentioned occur in the feldspars, but in the megascopic study of rocks they are not of importance.

Cleavage. All the different varieties of feldspar are alike in possessing a good cleavage in two directions, one parallel to the face *c* and another parallel to *b* (see Fig. 7). Since in orthoclase these two faces intersect at a right angle, so also do the cleavages, and it is from this fact that the name of the mineral is derived (Greek, ʼορθός, straight, right + κλᾶν, to break). In the lime-soda feldspars, albite to anorthite, these faces are slightly oblique, and so are the cleavage planes; hence the name plagioclase (Greek, πλάγιος, oblique + κλᾶν, to break) has been given to the group.

In rocks, if the feldspar grains are of good size, the cleavages are readily seen by reflected light; they are commonly interrupted, giving rise to step-like appearances. Even when the grains are small the cleavage can usually be detected with a lens in good light. Sometimes when the feldspars are more or less altered, as described under alteration, they lose more or less completely their capacity for showing good cleavage faces on a broken surface of the rock, and this fact must be taken into account in making determinations. In cleavage pieces as in the crystals that show distinct faces, the amount of obliquity of the plagioclases is too small to be used in distinguishing them from right-angled orthoclases by the eye or lens.

On a fractured rock surface, if the crystal grains are of sufficient size, the cleavages frequently show that they are twinned according to the Carlsbad method. The grain or broken crystal appears as if divided into two parts by a distinct line, called the twinning seam; on one side of this line, if it points away from the observer, the cleavage surfaces slope or step away in one direction; in the other half they slope toward the observer at an equal angle, like the two *c* faces in Fig. 8, to which indeed they are parallel. This difference in the cleavage directions in the two parts of the Carlsbad twin can usually be readily seen by shifting the position of the crystal in a good light until the reflections from the cleavage surfaces are obtained. At the same time, if examined with a good lens these surfaces may often be seen to be ruled by the fine parallel striations of the albite twinning, which indicates that the feldspar grain is a plagioclase.

Fracture. In directions in which they do not cleave, the fracture of feldspars is uneven and somewhat conchoidal. They are brittle.

Color, Luster, and Streak. Feldspars do not possess any natural color, hence, as explained under the color of minerals, they should normally be either limpid and colorless, or white. Transparent, colorless, glassy feldspars in rocks are confined to fresh and recent lavas, in which they may be frequently seen in the phenocrysts; they practically never occur in massive granular rocks like granites, gneisses, etc. In fresh lavas the luster may be strongly vitreous. More commonly, feldspars are semi-translucent or opaque and white, grayish white or yellowish, and of a somewhat porcelain-like appearance. Orthoclase and microcline commonly have a tinge of red; this color varies from a pale flesh tint to a strong brick-red or brownish red; a distinct flesh color is the shade most common. It is this color in the feldspars which gives many granites used for building stones their color. It is most probable that this variety of color is caused by finely disseminated ferric oxide dust which acts as a pigment, and it must be considered as an exotic and not a natural color. The plagioclases, or lime-soda feldspars, more rarely show this; they are commonly gray. The difference between the two classes of feldspars is apparently due to a difference in the chemical behavior of iron toward sodium and potassium; sodium enters readily into combination with iron in silicate minerals, while potassium does not. Thus in the potassium feldspars the iron would tend to be present as free oxide and to color the mineral. Therefore, rocks with potassic feldspars often tend to be of reddish color; those with sodic feldspars tend to be gray. This distinction may be used to some extent as an indicator of the kinds of feldspar, but it must never be taken as an absolute rule, because many potassic feldspars are white or gray, and, conversely, many instances occur where rocks with soda-lime feldspars are red. In general, one may say that if the rock contains two feldspars, one of which is red while the other is not, it is almost certain that the red feldspar is a potassic one or orthoclase.

The potassic feldspars, especially the variety called microcline, when occurring in distinct crystals in the miarolitic druses of granitic rocks have sometimes a green color, pale to bright grass-green. This is also an exotic coloration and is supposed to be due to some organic substance acting as a pigment, since it disappears on heating.

Sometimes the rock feldspars are gray, dark, smoky or bluish-gray, or even black. While this may happen with alkalic varieties, it is much more common with the soda-lime ones, especially labradorite. It is caused by a fine black dust disseminated through them, which acts as a pigment and which may sometimes be magnetite dust, but is much more often ilmenite. Fine examples of such feldspars are seen in the labradorite rocks from Canada, the Adirondack region in New York State, and Labrador, which have been called anorthosites. Sometimes these inclusions are of sufficient size and so regularly arranged in the feldspar that, by the interference of light, they produce an opalescence or play of colors in the mineral, as seen in the beautiful examples from St. Paul's Island on the coast of Labrador and from Kiev in Russia.

Other feldspars have a pearly bluish opalescence from innumerable minute cracks regularly arranged, which reflect light with interference colors.

The *luster* is vitreous, and on cleavages often pearly. Feldspars that are more or less altered commonly have a waxlike appearance and a waxy, glimmering luster; if completely altered they may look earthy and have no luster.

The *streak* is white and not characteristic.

Hardness. This is 6. Feldspar is scratched by quartz, scratches glass, but is not scratched by the knife.

Specific Gravity. Orthoclase = 2.54, albite = 2.62, anorthite = 2.76. The specific gravity of the various mixtures varies between these limits; thus the alkalic feldspars, which consist of a mixture of orthoclase and albite, average about 2.57, while the plagioclases vary regularly with the relative amounts of albite and anorthite, the specific gravity of labradorite being 2.67. If the specific gravity of a fragment of feldspar can be determined with accuracy to the second place of decimals, it affords a fairly good rough method of ascertaining the composition.

Chemical Composition. This is shown in the following table.

	SiO_2	Al_2O_3	CaO	Na_2O	K_2O	Total
I..........	64.7	18.4	....	....	16.9	100
II..........	68.7	19.5	....	11.8	....	100
III..........	43.2	36.7	20.1	....	....	100
IV..........	55.6	28.3	10.4	5.7	....	100

I, Orthoclase (and microcline); II, Albite; III, Anorthite; IV, Labradorite (equal mixture of albite and anorthite).

The mixtures vary naturally with the proportions of the pure products; an example of equal parts is given in IV. The other substances, such as iron oxide, etc., shown in feldspars by chemical analyses, are due to impurities.

Blowpipe and Chemical Characters. A fine splinter fuses before the blowpipe, with difficulty, to a globular ending, more easily in the case of anorthite and the varieties rich in anorthite than in that of albite and orthoclase. The flame shows the persistent yellow coloration of sodium; only occasionally do the rock feldspars prove to contain orthoclase that is pure enough to give the violet flame of potassium. Orthoclase and albite are not acted upon by ordinary acids to an appreciable extent; as the feldspars increase in calcium they become more soluble; thus labradorite is very slowly dissolved, while anorthite is slowly dissolved and affords gelatinous silica.

Alteration. Under the action of various agencies the feldspars are prone to be altered into other substances, which depend in part on the nature of the agents and in part on the composition of the feldspar attacked. Some of these changes and products are quite complex and their nature and significance have not as yet been sufficiently studied for us to understand them, but some of the simpler and more important ones are as follows.

When the feldspars are acted upon by water carrying carbonic acid gas in solution, which may happen with surface waters leaching downward or with hot waters rising from depths below, they may be turned into kaolin or muscovite with separation of free silica and alkaline carbonates. These changes may be expressed chemically as follows:

$$\begin{array}{llllll} \text{Orthoclase} + \text{Water} + & \text{Carb. diox.} & = \text{Kaolin} & + \text{Quartz} + & \text{Potas. Carb.} \\ 2\,KAlSi_3O_8 + 2\,H_2O + & CO_2 & = H_4Al_2Si_2O_9 & + 4\,SiO_2 + & K_2CO_3 \\ \text{Orthoclase} + \text{Water} + & \text{Carb. diox.} & = \text{Muscovite} & + \text{Quartz} + & \text{Potas. Carb.} \\ 3\,KAlSi_3O_8 + H_2O + & CO_2 & = H_2K(AlSiO_4)_3 & + 6\,SiO_2 + & K_2CO_3 \end{array}$$

What determines whether the removal of the potassium from the feldspar will be complete, so that kaolin is formed, or only partial, so that muscovite is the resultant product, is not clearly understood. In a general way, one may say that weathering from the action of surface waters generally forms kaolin, while the change to muscovite is more likely to be a deep-seated affair and is especially noted in processes of metamorphism. In mines it is often seen that the solutions which deposited the ores have altered the rocks enclosing them, sometimes to kaolin, sometimes to a form of muscovite (sericite), and sometimes to other products. It is due to this in great part that such rocks are so often changed from their original fresh condition.

All feldspars undergo changes similar to those mentioned, but in those feldspars which contain calcium the alterations are more complex, since calcite, the carbonate of calcium, is also formed. Accordingly, as this change to muscovite or kaolin is more or less complete, the feldspars lose their original bright appearance and become dull and earthy in character; if the change is pronounced, they are soft and may be cut or scratched with the knife or even with the finger nail. As a result of certain changes, the lime-soda feldspars take on a faint, glimmering luster, become semi-translucent, often of a pale bluish or grayish tone, lose to a great extent their property of cleavage, and resemble wax or paraffin as mentioned under cleavage. Often these changes do not take place regularly through the whole mass of the crystal; sometimes the border is altered, sometimes the center only is attacked, and sometimes, especially in the lime-soda ones, like labradorite, zones between the two are altered. If the feldspars of a rock do not show bright, glistening cleavage surfaces, it may be considered practically certain that they are more or less altered. These alterations of the feldspars are of great importance in geologic processes and especially in the formation of soils.

In addition to these alterations, others also are known; thus under some circumstances the feldspars are changed into zeolites, and in metamorphic processes the feldspars containing calcium may react with other minerals to form epidote, garnet, etc., changes which are mentioned elsewhere.

Occurrence. The feldspars are of wide distribution, more so than any other group of minerals. They are found in all classes of rocks: in most of the igneous ones, such as granites, syenites, porphyries, and felsite lavas; in the sedimentary ones in certain kinds of sandstones and conglomerates; and in the metamorphic rocks in gneisses. Since, so far as our knowledge extends, the crust of the Earth, underlying all the sedimentary beds of all ages deposited upon it, is composed chiefly of granites, gneisses, etc., in which feldspars are the main minerals, it is not too much to say that there is more feldspar in the world than any other substance of the occurrence of which we have knowledge.

Determination. In general, the two cleavages at right angles or nearly so, the vitreous luster, the light color, and the hardness, which resists the point of the knife, enable one in the field to recognize the feldspar grains of rocks and to distinguish them from the other common minerals, especially quartz, with which they are usually associated. Sometimes the crystal form may also be of assistance, especially in porphyries. In addition, one or more of the various chemical and physical properties enumerated above may be determined on separated fragments, if the feldspar grains or masses are of sufficient size.

The determining of the different varieties of feldspar which may be present in a rock is, however, a much more difficult task when only megascopic means are employed. Sometimes the remarks made under the heading of color will be of assistance. If the cleavage surfaces are closely examined with a lens and the fine lines of striation of the albite twinning are found, then one knows that a plagioclase feldspar is present, since orthoclase cannot have this twinning, as previously explained. The only practical exception to this rule is that the large, often huge, crystals of potassium feldspar in granite-pegmatite dikes are often not really orthoclase but microcline, a triclinic variety, and a good cleavage surface of this examined in a strong light with a powerful lens frequently shows a minute, scarcely perceptible, multiple twinning like the albite twinning.

If no multiple twinning is seen it would not therefore be safe to conclude that the feldspar is necessarily an orthoclase and not a plagioclase, because this twinning, as already stated, is often so fine that it cannot be detected with the lens and is sometimes wanting. As the grain of rocks grows finer it becomes increasingly difficult to detect, but a good training of the eye by studying a series of rocks in which it is present in the feldspars is a great help and eventually enables one to perceive it clearly where at first it could not be seen. The modern tendency on the part of geologists to refer all difficulties in rocks to microscopic examination of thin sections has led to a great neglect in the training of the eye for megascopic determination of minerals in rocks, and to a corresponding loss of efficiency in the field.

If the albite twinning is clearly seen in several of the feldspar grains of a rock it may be quite safely concluded that a considerable proportion of plagioclase is present; this may, indeed, be practically the only feldspar present. If albite twinning cannot be seen, plagioclase may or may not be present.

Other means which may be resorted to are the determination of the specific gravity, the behavior before the blowpipe, and with acids, as previously mentioned, and the chemical tests for sodium, potassium, and calcium, which suggest themselves to those experienced in analytical chemistry. Further information on the subject should be sought in the special manuals devoted to determinative mineralogy.

The Feldspathoid Group

The feldspathoid group owes its name to the fact, that, like the feldspars, it is composed of minerals that are silicates of aluminum with sodium, potassium, and calcium and that are found in the same associations, accompanying or replacing feldspars and playing a similar part in the making of rocks. Unlike feldspars, the minerals of the feldspathoid group are comparatively rare and are restricted entirely to certain kinds of igneous rocks, such as nephelite syenite. Thus in a discussion of the occurrence of common rocks they are, compared with the feldspars, of relatively much less importance, but if one is dealing with questions regarding the origin of igneous rocks, they are of great significance. The more important members of the group are *nephelite* and *sodalite;* less common ones are *noselite* and *hauynite*, *cancrinite*, and *leucite.*

Nephelite. This mineral crystallizes in short, thick, hexagonal prisms or tables with a flat base and top, but it rarely shows distinct crystal form in rocks. Most commonly it occurs in shapeless masses and grains, like quartz. Its normal color is white, but it is usually gray, varying from light smoky to dark in tone; sometimes it is flesh-colored or brick-red.

The white color may shade into yellowish, the gray into bluish or greenish. The streak is light — not characteristic. The mineral is translucent; its luster, when fresh, is oily or greasy. Like quartz it has no good cleavage and its fracture is somewhat conchoidal. It is brittle. The hardness is nearly that of feldspar = 6; specific gravity, 2.55–2.61. Its composition is chiefly $NaAlSiO_4$ with a small, varying amount of potassium replacing sodium. Before the blowpipe a fine splinter fuses quite readily to a globule, tingeing the flame deep yellow. Nephelite is readily soluble in dilute acid with formation of gelatinous silica.

Sodalite. The form of crystallization is the isometric dodecahedron, so often seen in garnet, but this is rarely seen in rocks, the mineral commonly occurring in formless grains and lumps. It is sometimes white, pink, or greenish gray, but the usual color is a blue of some shade, often a bright sky blue to dark rich blue. The blue color may be due to a slight admixture of the lapis-lazuli molecule acting as a pigment. Sodalite is usually translucent. Cleavage is dodecahedral but not striking as a megascopic property; fracture uneven to poorly conchoidal; luster, vitreous to greasy; streak, white; hardness, nearly that of feldspar, 5.5–6; specific gravity, 2.15–2.30. Its composition is $Na_4(AlCl)Al_2(SiO_4)_3$ and this may also be expressed $3\ NaAlSiO_4 . NaCl$, but it should not be understood from this that sodalite consists of a mixture of nephelite and common salt molecules; it is a definite chemical compound into which the chlorine enters. Sodalite fuses rather easily before the blowpipe, with bubbling, coloring the flame yellow. It is easily soluble in dilute acids with formation of gelatinous silica; in the nitric acid solution, the test for chlorine with silver nitrate may be applied.

The other feldspathoids are less common and, in their general properties, modes of occurrence, and functions as rock minerals, are similar to nephelite and sodalite, which they usually accompany or in part take the place of.

Hauynite and Noselite. These show characters like sodalite but they differ from it in containing the radical SO_4 of sulphuric acid in the place of chlorine. The best method of detecting them is by the test for sulphuric acid with barium chloride in their nitric acid solution. They differ from each other only in the fact that noselite is the pure sodium compound, while in hauynite a part of the sodium is replaced by calcium.

Cancrinite is much like nephelite in its general properties. It contains CO_2 in combination, which aids in detecting it, as explained later in the directions for testing minerals and rocks. Its formula might be written $8\ NaAlSiO_4 . CaCO_3 . CO_2 . 3\ H_2O$, but, as in sodalite, it is not a mixture of molecules but a definite compound. The color is variable but is frequently a bright yellow to orange, which may also help in detecting it. Cancrinite is believed to have been formed, in some cases, by the alteration of nephelite, but usually, if not always, it is an original mineral crystallizing from a molten magma, like nephelite and feldspar.

Leucite is a rare feldspathoid crystallizing in isometric trapezohedrons, a form illustrated in garnet; the crystals, when imperfect, appear spherical. Its cleavage is imperfect; fracture, conchoidal; color, white to gray; luster, vitreous. Hardness is 5.5–6; specific gravity, 2.5. Before the blowpipe it is infusible and when mixed with powdered gypsum gives the flame the violet color of potassium. It dissolves in acids without gelatinizing. Its composition is $KAl(SiO_3)_2$. It occurs almost wholly in lavas and is nowhere common except in those of central Italy and Java, where the magmas are characterized by a high content of potash. The most noted occurrence is in the lavas of Vesuvius, in some of which leucite is found in good-sized, well-shaped crystals of the form illustrated in Fig. 31 under garnet. Large crystals, altered, however, to other minerals, have been found in certain syenites and related rocks in Arkansas, Montana, Brazil, and elsewhere.

Alteration. The feldspathoids, like the feldspars, are liable to alteration from the processes of weathering when exposed to the atmosphere and to the action of fluids circulating in the rocks at lower levels. They become converted into kaolin or muscovite and also, very commonly, into zeolites. The alteration into zeolite occurs very generally; all that is necessary is a rearrangement of the molecule and the assumption of water and silica; hence when the feldspathoids are heated in a closed glass tube they are very likely to yield water. Thus

Nephelite and silica and water yield analcite.

$$NaAlSiO_4 + SiO_2 + H_2O = NaAl(SiO_3)_2 . H_2O.$$

The *determination* of the feldspathoids in rocks is best done by chemical means. With the exception of leucite, which is too rare a mineral to be considered except in very unusual cases, they yield gelatinous silica and may be tested for as described later under mineral tests. Nephelite is easily confused with quartz, which it often closely resembles in rocks; its association with other minerals and the appearance of those rocks in which it chiefly occurs, and which are described in their appropriate places, help in arousing suspicion of its presence, and this is readily confirmed by its solubility in acids. Fortunately for field determinations, nephelite is a very rare mineral, quartz an exceedingly common one; thus the assumption that the mineral is quartz in the vast majority of instances will be right.

Micas

The micas form a natural group of rock minerals which is characterized by great perfection of cleavage in one direction and by the thinness, toughness, and flexibility of the elastic plates, or laminæ, into which this cleavage permits them to be split. For practical purposes of megascopic rock study and classification, they can be divided into two main groups, *light*-colored micas, or *muscovite* and related varieties, and *dark*-colored *biotite* and related varieties.

Form. Micas crystallize in six-sided tablets with flat bases. These tablets appear to be short hexagonal prisms (see Fig. 17); in reality, as may be shown by optical methods, their crystallization is monoclinic. Their side faces are rough and striated, the flat bases, which are usually cleavage faces, bright and glittering. Sometimes two of the side faces are much elongated, as in Fig. 18. While distinct crystal form is often observed in rocks, particularly the igneous ones, the micas are much more commonly seen in shapeless flakes, scales, or shreds, with flat,

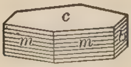

Fig. 17

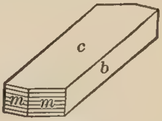

Fig. 18

shining, cleavage faces. Sometimes the folia, or leaves, are curled or bent.

Cleavage. This has already been mentioned. The cleavage is perfect in a direction parallel to the base. It is this property, combined with the flexibility, transparency, and toughness of the mineral, that makes the large crystals and sheets of muscovite, found in pegmatite veins, so useful in making stove windows, lamp chimneys, etc., where ordinary glass is easily broken. Sometimes when the mineral occurs as an aggregate of minute scales, especially when muscovite occurs in the sericite form, the cleavage is not so apparent, but it can generally be seen by close observation.

Color, Luster, and Hardness. Muscovite is colorless, white to gray or light brown, often with greenish tones. The other light-colored micas are similar, except that lithium mica, or lepidolite, found in pegmatite veins, is usually pink or lilac-colored. These micas in thin sheets are transparent.

Biotite and its congeners are black; in thin sheets they are translucent, with strong brown, red-brown, or deep green colors. The phlogopite variety is pale brown, sometimes coppery. The luster of micas is splendent, on cleavage faces sometimes pearly, and in the sericite variety of muscovite frequently silky. The hardness varies from 2 to 3; all are easily scratched with the knife.

Chemical Composition. Chemically, the micas that take part in rock-making may be divided into two main groups: one, of which the dark-colored biotite is an example, containing iron and magnesium, the other, of which muscovite is the most prominent member, devoid of these elements. They are complex in composition, being silicates of aluminum with alkalies, and containing more or less hydroxyl and fluorine. The two main varieties may be represented as follows:

$$\text{Muscovite} = H_2KAl_3(SiO_4)_3.$$

$$\text{Biotite} = (H,K)_2(Mg,\overset{\cdot\cdot}{Fe})_2(Al,\overset{\cdot\cdot\cdot}{Fe})_2(SiO_4)_3.$$

The other members of the muscovite group are *paragonite*, a rare mineral resembling muscovite, in which sodium replaces potassium; and *lepidolite*, in which the potassium of muscovite is partly replaced by lithium. In the biotite sub-group, *phlogopite* is a variety nearly free from iron and is thus a magnesian mica; the lack of iron accounts for its lighter color. *Lepidomelane*, on the contrary, is very rich in iron, especially ferric iron, while another variety, *zinnwaldite*, contains some lithium in place of part of the potassium. The formulas of these compounds are very complex and in part not absolutely settled. The following table of analyses shows the chemical differences between the varieties.

	I	II	III	IV	V	VI	VII
SiO_2.....	44.6	46.8	48.8	36.0	39.6	32.1	45.9
Al_2O_3....	35.7	40.1	28.3	18.8	17.0	18.5	22.5
Fe_2O_3....	1.0	....	0.3	5.6	0.3	19.5	0.6
FeO.....	1.0	....	0.1	14.7	0.2	14.1	11.6
MgO.....	....	0.6	....	9.8	26.5	1.0	....
CaO.....	0.1	1.3	0.1	0.6	....	....	....
Na_2O....	2.4	6.4	0.7	0.4	0.6	1.5	....
K_2O.....	9.8	....	12.2	9.3	10.0	8.1	10.5
Li_2O.....	....	....	4.5	....	....	....	3.3
H_2O.....	5.5	4.8	1.7	2.5	3.0	4.6	0.9
F........	0.7	....	5.0	0.3	2.2	....	7.9
X*......	....	....	....	1.9	1.2	1.4	1.7
Total....	100.8	100.0	101.7	99.9	100.6	100.8	104.9

* X represents small quantities of non-essential oxides present.

I, Muscovite, Auburn, Me.; II, Paragonite, the Alps; III, Lepidolite, Hebron, Me.; IV, Biotite, from granite, Yosemite, Cal.; V, Phlogopite, Burgess, Ontario; VI, Lepidomelane, from nephelite syenite, Litchfield, Me.; VII, Zinnwaldite, Zinnwald, Erzgebirge.

Blowpipe and Chemical Characters. Usually the micas whiten before the blowpipe and fuse on the edges, when in thin scales. Lepidomelane fuses to a black, magnetic globule. Heated in the closed glass tube, they yield very little water, which helps to distinguish them from chlorites and other micaceous rock minerals. When thin scales are treated with a little boiling concentrated sulphuric acid in a test tube, muscovite and the related light-colored kinds are scarcely acted upon, but biotite and its congeners are decomposed, the scales losing their luster and transparency while the acid becomes turbid.*

Lepidomelane is soluble in hydrochloric acid, depositing silica in scales. This is an important character serving to distinguish it from the other micas. The lithium micas impart a red color to the blowpipe flame, while paragonite imparts the yellow color of sodium.

Alteration. Biotite under the action of weathering becomes leached of its bases, loses its elasticity, and becomes soft and eventually decolorized. Muscovite, being itself often the product of various alterations of other minerals, especially of feldspars, appears well fitted to withstand the process of weathering, and its scales often occur in soils made of broken-down rocks the other constituents of which may be greatly changed. It eventually changes, loses its transparency and elasticity, and perhaps becomes ultimately converted into clay.

Occurrence. The common micas are minerals of wide distribution as rock components. *Biotite* is a very common and prominent ingredient of many igneous rocks, especially of those rich in feldspar, like granites and syenites. In ferromagnesian rocks like gabbro, it is less prominent. It is also seen in many felsite lavas and porphyries. It occurs commonly in some metamorphic rocks, such as gneisses and schists, and is frequently one of the products of contact metamorphism exerted by igneous rocks. Because it alters easily it does not figure as a component of sedimentary beds. The *phlogopite* variety, containing little iron, has been found in some rare instances in igneous rocks, but it occurs chiefly as a product of metamorphism in crystalline limestones or impure marbles and

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* Care should be used in making this test not to bring the hot acid in contact with water, or the mixture will take place with explosive activity.

dolomites. *Lepidomelane* and *zinnwaldite* appear to occur chiefly in granites and syenites, especially in pegmatitic varieties. *Muscovite* occurs in granites and syenites, especially in pegmatite veins and in miarolitic druses, and in places where the igneous rocks have been subjected to later fumarole action, which has furnished water and fluorine. It occurs rarely in intrusive porphyries. It is especially common in the metamorphic rocks and is widely distributed in gneisses and schists; sometimes, especially in the latter rocks, it is in the form of an aggregate of minute scales which have a silky luster and largely lack in appearance the evident characters of the mineral, such as its cleavage; this variety has been called *sericite*. When feldspars are altered to muscovite rather than to kaolin, this sericite variety is the common product. In the sedimentary rocks, such as conglomerates and sandstones, muscovite is sometimes seen, an unchanged remnant of the original rocks from which their material came. *Lepidolite* is practically restricted to granite-pegmatite veins and is constantly accompanied by tourmaline. *Paragonite* has been found in only a few places, in schists, playing the rôle muscovite would ordinarily have.

Determination. From the ordinary rock minerals the micas are at once distinguished by their appearance, high luster, and eminent cleavage, the last-named quality and their hardness being readily tested in the field by the knife point. From the chlorite group and from talc, which resemble them, they are distinguished by the elasticity of their split-off laminæ, those of the chlorites and talc being flexible but not elastic. From *chloritoid*, a micaceous-appearing mineral of a gray or green color, a hydrated silicate of aluminum, magnesium, and iron, which is sometimes seen in distinct crystals in certain metamorphic rocks, they are readily distinguished because of the superior hardness (6.5) and brittleness of chloritoid. The different varieties of mica are best discriminated by the chemical and blowpipe tests already mentioned.

Pyroxenes

The pyroxene group embraces a number of important minerals which have two properties in common: (1) they are metasilicates, salts of metasilicic acid, H_2SiO_3, in which the hydrogen is replaced by various metals as shown later; and (2) although they may differ in the system in which they crystallize, they have closely related crystal form, notably a prismatic cleavage of 87° and 93°. As rock minerals they are of greatest importance in the igneous rocks, though they may be prominent in some of the metamorphic ones. Some igneous rocks are composed almost entirely of pyroxene.

It is often difficult to recognize pyroxene in the rocks and distinguish it from several other minerals purely by simple megascopic methods; and it is generally impossible to tell from one another, by such means, the many varieties recognized by mineralogists and petrographers. The differences between these varieties are chiefly in chemical composition and optical properties and these must be determined by chemical and optical methods.

For practical megascopic petrography the pyroxenes may be divided into the following sub-groups dependent on their color, behavior before the blowpipe, and chemical reaction for calcium, as described later: *hypersthene*, *diopside*, *common pyroxene*, *augite*, and *ægirite*.

Form. Hypersthene crystallizes in the orthorhombic, the others in the monoclinic systems, but this distinction is not a matter of practical importance in megascopic work, since hypersthene is rarely well enough crystallized to enable one to determine its system. The common form in which the monoclinic rock pyroxenes crystallize is a prism, usually short and thick though sometimes longer and more slender. Such a prism is shown in Fig. 19, the ends modified by pyramidal faces. Generally, however, the edges of the prism *mm* are truncated by a front face *a* and a side face *b*; sometimes these truncations are small so that *a* and *b* are slender (Fig. 20); often they are very broad and *mm* narrow. While these faces are commonly well developed and often lustrous, the pyramidal faces are often very imperfect or wanting, the crystal being rounded at the ends; rarely, other pyramidal faces are present and the ends much more complex than in the figures. The augites which occur in igneous rocks, especially porphyries and lavas, very often have the appearance and development shown in Fig. 21. The most important feature of the crystallization is that the angle *m* on *m* is nearly a right angle, 87°, so that the prism is nearly square in cross section, or, when truncated by *a* and *b*, octagonal as shown in Fig. 22. Besides occurring in prismatic crystals the pyroxenes are very common in grains, or in more or less shapeless masses; this is usually true in certain massive igneous rocks such as gabbros and peridotites.

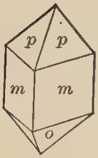

Fig. 19

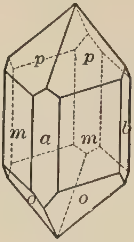

Fig. 20

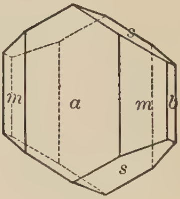

Fig. 21

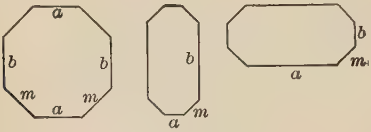

Fig. 22

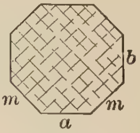

Fig. 23

Cleavage and Fracture. As previously mentioned, the pyroxenes have a cleavage parallel to the faces *mm*, nearly at right angles, as shown in Fig. 23; this is fundamental and serves to distinguish the mineral from hornblendes. This cleavage is usually very good but not perfect. Some varieties often have a good parting, resembling cleavage, in other directions, which causes the mineral to appear lamellar, perhaps even somewhat micaceous, as seen in the pyroxenes of some gabbros. Fracture is uneven; the mineral is brittle.

Color and Luster. The color varies from white through various shades of green to black, according to the amount of iron present. The pure diopsides are white, rarely colorless and transparent, often pale green, and more or less translucent. Common pyroxenes are dull green of various shades. Augite and ægirite are black and opaque. The luster, which is often wanting, is glassy to resinous. Streak varies from white to gray-green.

Hardness and Specific Gravity. The hardness varies from 5 to 6. Some varieties can just be scratched by the knife. The specific gravity varies, chiefly with the iron present, from 3.2 to 3.6.

Chemical Composition. Pyroxenes are composed of the metasilicate molecules $\mathrm{MgSiO_3}$, $\ddot{\mathrm{F}}\mathrm{eSiO_3}$, $\mathrm{CaMg(SiO_3)_2}$, $\mathrm{Ca\ddot{F}e(SiO_3)_2}$, $\mathrm{Na\ddot{F}e(SiO_3)_2}$, and $\dddot{\mathrm{R}}\mathrm{_2O_3}$, in the last of which $\dddot{\mathrm{R}} = \mathrm{Al}$ and $\dddot{\mathrm{F}}\mathrm{e}$. These molecules are capable of crystallizing in various mixtures which produce the same crystal form and many similar physical properties. The *hypersthene* sub-group contains mixtures of $\mathrm{MgSiO_3}$ and $\mathrm{FeSiO_3}$ without lime; *diopside* is $\mathrm{CaMg(SiO_3)_2}$ with little or none of the iron molecule; *common pyroxene* contains variable mixtures of $\mathrm{CaMg(SiO_3)_2}$ (diopside) and $\mathrm{CaFe(SiO_3)_2}$ (hedenbergite) with small portions of the other molecules; *augite* contains the same but in addition a large amount of $\dddot{\mathrm{R}}\mathrm{_2O_3}$; *ægirite* is mostly $\mathrm{Na\dddot{F}e(SiO_3)_2}$ and is thus a sodium pyroxene.

Blowpipe and Chemical Characters. Hypersthene varies in fusibility, being almost infusible in the blowpipe flame when it contains little iron (variety enstatite) and fusible with difficulty when it contains much iron; in the latter case it becomes black and slightly magnetic. The other pyroxenes are much more fusible (= 4) and melt quietly or with little intumescence to glassy globules the color of which depends on the amount of iron: diopside nearly colorless; common pyroxene green or brown; augite and ægirite black; the last two magnetic. Ægirite fuses quietly and colors the flame yellow. They are but slightly acted upon by acids, those with iron more so than those without.

These differences in the chemical composition are shown in the table of analyses.

	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	X*	Total
I.......	53.1	1.0	....	17.8	24.8	2.7	....	0.4	99.8
II......	58.0	1.3	....	3.1	36.9	....	....	0.8	100.1
III.....	55.1	0.4	....	1.1	18.1	25.0	0.4	0.2	100.3
IV......	51.1	2.0	1.3	12.3	10.0	22.1	....	0.4	99.2
V.......	47.0	9.8	4.5	4.1	16.0	19.0	....	....	100.4
VI......	51.4	1.8	23.3	9.4	0.3	2.0	11.9	0.1	100.2

* X = small quantities of other oxides.

I, Hypersthene, Romsaas, Norway; II, Hypersthene (var. enstatite), Bamle, Norway; III, Diopside, DeKalb, N. Y.; IV, Common pyroxene, Edenville, N. Y.; V, Black augite, Vesuvius lava; VI, Ægirite, from syenite, Hot Springs, Ark.

Alteration. The pyroxenes are prone to alter into other substances, the nature of which depends partly on the kind of process to which they are subjected and partly on their own composition. Thus under the action of weathering they may be converted into carbonates, such as calcite. Pyroxenes containing much iron may break down completely into hydrated iron oxides, such as limonite, and carbonates.

Another very important change is one that they suffer under metamorphic processes, especially regional ones. In this they become altered to masses of fibrous, felty or stringy hornblende needles and prisms, usually of distinct but variable green colors. This process is of great geologic importance, for by means of it whole masses of pyroxenic rocks, generally of igneous origin, such as gabbros, peridotites, basalts, etc., have been changed into hornblendic ones to which a variety of names, such as greenstone, greenstone schist, hornblende schist, etc., have been applied. The process is further mentioned under metamorphism, and under gabbro, dolerite, greenstone, and amphibolite.

Occurrence. The pyroxenes occur chiefly in igneous rocks, especially those formed from magmas rich in lime, iron, and magnesia. Therefore, one should always look for them in the dark-colored rocks of this class. They are not often found in igneous rocks that contain much quartz; hence in granites, felsite porphyries, and felsite lavas they are rare. Augite is found in basaltic lavas and dark, trap-like intrusives, often in well-formed crystals; when it occurs in gabbros and peridotites it is commonly in grains and lumps. Hypersthene is prominent in masses and grains in some varieties of gabbro and peridotite. Ægirite occurs chiefly in nephelite syenites and the phonolite variety of felsite lava. Some normal syenites and related rocks contain diopside-like or common pyroxene. In the metamorphic rocks, common pyroxene and diopside, the latter sometimes white or pale greenish and transparent, are found in impure recrystallized limestones and dolomites, sometimes in well-formed scattered crystals, sometimes aggregated into large masses. Common pyroxene also occurs in some gneisses. Being readily decomposed by weathering, pyroxenes play no part in sedimentary beds.

Determination. If the mineral under examination is in well-formed crystals, careful observation will usually show whether or not it is a pyroxene by the presence or absence of the forms previously described. The outline of the section presented by the prisms, especially when broken across, should be noted in this connection. The common minerals in rocks with which pyroxenes may be confused are hornblende, epidote, and tourmaline. The lack of good cleavage, the superior hardness, the high luster, dense black color, and triangular shape of the prism cross section of tourmaline readily distinguish it from pyroxene. Epidote has one perfect cleavage, one poor one; it is much harder, 6 to 7; while green, it commonly has a yellow tone, giving a yellowish green; before the blowpipe it intumesces when fusing. The distinction between pyroxene and hornblende is more difficult to recognize and is treated in the section devoted to hornblende.

To distinguish the different varieties of pyroxene from one another, the blowpipe tests previously mentioned should be used in conjunction with the natural color of the mineral. The hypersthenes are distinguished from other pyroxenes by making a chemical test to prove the absence of calcium or its presence in only minute quantity. This test is best done by making a small fusion with soda as described in the chapter treating of mineral tests.

The most expeditious and certain way of distinguishing the several pyroxenes is the immersion method, in which the minerals are examined optically in oils of known refractive indices.

Amphiboles

The amphiboles are a natural group of silicate minerals which, like the pyroxenes, are salts of metasilicic acid, H_2SiO_3, in which the hydrogen is replaced by various metals or radicals. They have in common a certain crystal form and a prismatic cleavage of about 55°, and are nearly related in many physical properties. As in the pyroxene group, to which the amphiboles are closely allied in several ways, petrographers recognize many varieties dependent upon differences in chemical composition and physical properties, especially optical ones, which are impossible to distinguish by the unaided eye and many of which cannot be distinguished by ordinary megascopic tests.

For practical work in megascopic petrography the amphiboles may be divided into the following sub-groups: *tremolite, actinolite, common hornblende,* and *arfvedsonite.* These may be distinguished by their colors, associations, and behavior before the blowpipe.

Form. Amphiboles crystallize in the monoclinic system. The crystals are usually long and bladed, formed by two prisms *mm* which meet at angles of 55° and 125°. Sometimes there are terminal faces *rr* as in Fig. 24, sometimes the crystals are imperfect at the ends and no terminal faces are seen; this latter condition is common in rocks. Very often the side face *b* is present, truncating the prism edge, and the crystal has a nearly hexagonal cross section as in Fig. 25. More rarely the front face *a* is present as in Fig. 26. The black hornblendes found as phenocrysts in some basaltic rocks often have a not very short prism and appear as in Fig. 27; these are the hornblendes that most often have distinct terminal planes. The prismatic faces *mm* and the face *b*, if it is present, tend to be shining, and the ends are frequently dull. It is not common for amphibole to present itself in rocks in crystals of which the planes can be distinctly seen; when this occurs it is mostly in the black hornblendes found in lavas as phenocrysts and in those occurring in limestones and dolomites that have been subjected to metamorphism. The common appearance is in long, slender blades with irregular, rough ends; this is usual in the hornblende schists where the crystals are aggregated together in more or less parallel position. They may dwindle in size to shining needles, becoming so fine that the minute prisms can hardly be seen with the lens; the aggregate then has a silky appearance. In the felsitic lavas and porphyries the prisms of the hornblende phenocrysts vary from rather short forms, like those in the figures, to slender needles; in the massive doleritic rocks like diorite, the amphibole is likely to occur in irregular grains and small masses. Sometimes, as in *asbestos*, the mineral has a highly developed columnar, fibrous form.

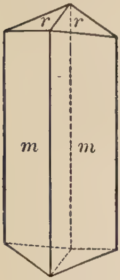

Fig. 24

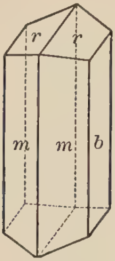

Fig. 25

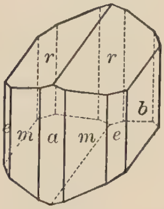

Fig. 26

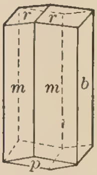

Fig. 27

Cleavage. Amphiboles have a highly perfect cleavage parallel to the prism faces *mm*, as illustrated in the cross section, Fig. 28. Like the faces *mm*, these cleavages meet at angles of 125° and 55°, a fact of great importance in distinguishing the mineral. The glittering prismatic faces seen on the blades and needles of fractured rock surfaces are commonly due to this good cleavage. The fracture is uneven.

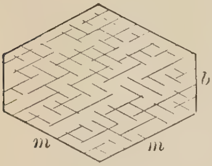

Fig. 28

Color and Luster. The color varies with the amount of iron: from white or gray in tremolite to gray-green or bright green in actinolite to darker greens and black in common hornblende. Arfvedsonite is black. Some varieties of amphibole found in igneous rocks appear black but are really deep brown. The mineral varies from opaque in the deeper-colored varieties to translucent in the lighter ones. The luster is bright and vitreous to somewhat pearly on the cleavage surfaces; in very fine, needle-like or fibrous varieties, silky. The streak is white to gray-green or brownish.

Hardness and Specific Gravity. The hardness varies from 5 to 6; some specimens can be scratched with the knife. The specific gravity varies, chiefly with the amount of iron, from 2.9 to 3.5.

Chemical Composition. Amphiboles, like the pyroxenes, are metasilicates, salts of H_2SiO_3, in which the hydrogen atoms are replaced by calcium, magnesium, iron, sodium, and also, as shown by Penfield, by radicals in which aluminum plays a prominent part and which contain hydroxyl ($-$ OH) and fluorine. Penfield has also shown that when calcium is present it replaces one fourth of the hydrogen atoms. Thus, while the amphiboles resemble the pyroxenes in being metasilicates and composed of the same elements, they differ from them in being much more complex and in containing hydroxyl and fluorine. Their compositions, as a rule, are too complicated to be represented by simple formulas, but in a general way, disregarding the hydroxyl and fluorine, one may say that each type of pyroxene has a corresponding amphibole, and in this connection the composition of the pyroxenes should be studied.

Thus, *tremolite,* if simply represented by $CaMg_3(SiO_3)_4$, corresponds to diopside, $CaMg(SiO_3)_2$; while *actinolite,* $Ca(Mg,Fe)_3(SiO_3)_4$, with variable amounts of ferrous iron replacing magnesium, corresponds to common pyroxene, $Ca(Mg,Fe)(SiO_3)_2$. *Common hornblende,* or *hornblende* for short, which consists of the actinolite molecule with others in which radicals containing aluminum or ferric iron and usually both are present, with perhaps some alkalies, corresponds in general to augite, which is a variable mixture of pyroxene molecules with alumina and ferric oxide. *Arfvedsonite,* which contains chiefly sodium, calcium, and ferrous iron, plays the part of ægirite, the sodium-iron pyroxene, though a very rare variety, riebeckite, more nearly corresponds in composition.

Glaucophane is a rare variety of amphibole, consisting of a mixture of a sodium-aluminum molecule with a cummingtonite molecule,

$$NaAl(SiO_3)_2 . (Mg,Fe)SiO_3.$$

It is distinguished from other hornblendes by its blue color, often a rich sky-blue or lavender-blue. It occurs only in a rare variety of amphibole schists, called glaucophane schists, which are described under amphibolites.

The chemical composition of the amphiboles is illustrated in the following table of analyses.

	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	H_2O	F_2	XyO*	Total
I....	57.5	1.3	0.2	0.2	24.9	12.8	0.7	1.3	0.8	0.6	100.3
II...	56.1	1.2	0.8	5.5	21.2	12.1	0.2	1.9	0.1	0.6	99.7
III..	41.9	11.7	2.5	14.3	11.2	11.5	2.7	0.7	0.8	2.6	99.9
IV ..	43.8	4.4	3.8	33.4	0.8	4.6	8.1	0.1	...	1.5	100.5
V ...	55.6	15.1	3.1	6.8	7.8	2.4	9.3	...	...	0.5	100.6

* XyO = small quantities of minor components.

I, Tremolite, Richville, Gouverneur, New York; II, Actinolite, Greiner, Tyrol; III, Hornblende, Edenville, Orange County, New York; IV, Arfvedsonite, Kangerdluarsuk, Greenland; V, Glaucophane, Island of Syra, Greece.

Blowpipe and Chemical Characters. Tremolite, actinolite, and common hornblende melt quietly or with little intumescence before the blowpipe, fusing rather easily at 4. The color of the bead depends on the amount of iron, tremolite being nearly colorless; actinolite, green or brown; common hornblende, dark and shining. Common hornblende sometimes colors the flame yellow, indicating sodium. Arfvedsonite fuses easily (3.5), colors the flame a strong, persistent yellow, intumesces decidedly (thus differing from ægirite), and yields a black, shining, magnetic bead. The amphiboles are only slightly attacked by the ordinary acids, those rich in iron more than those without.

Alteration. The amphiboles alter similarly to the pyroxenes. Under the action of various agencies they may be changed into serpentine or into chlorite or into both, accompanied by the formation of carbonates, sometimes of epidote and also of quartz. Under the continued action of weathering they may break down further into limonite, carbonates, and quartz. Thus on much-weathered rock surfaces, only rusty-looking holes and spots may be left to show the former presence of amphiboles.

Occurrence. Amphiboles are common and widely distributed minerals playing an important rôle in igneous rocks and especially in the metamorphic ones. The presence of water, hydroxyl, and fluorine in the amphiboles shows that they are not formed by simple reactions like the pyroxenes but require the presence of mineralizing vapors. Thus they cannot be artificially formed by allowing simple dry fusions containing their constituent silica and metallic oxides to cool and crystallize; pyroxenes are produced instead. Moreover, if hornblendes are fused and the melt allowed to crystallize, we obtain pyroxenes, magnetite, etc., in their place; this is because the necessary water and fluorine have escaped.

Tremolite is found chiefly in the impure crystalline limestones and dolomites in the schistose metamorphic rocks and in contact zones. In such occurrences it not infrequently has an extraordinarily fine fibrous structure and is capable of being split into long, flexible fibers of great fineness and strength, forming the greater part of what is known as *asbestos*. Sometimes actinolite and other amphiboles are found in this asbestos form. Most of the so-called asbestos of commerce, however, is really a fibrous variety of serpentine.

Actinolite has its true home in the crystalline schists; it is the characteristic light green to bright green amphibole of many amphibole schists and greenstones: in many of these it is secondary after the original pyroxene of former gabbro and trap rocks, as described under uralite.

Common *hornblende* occurs both in igneous and metamorphic rocks. It is found in granites, common syenites, and in the doleritic types; also in diorite and some varieties of peridotite. It may often be observed in the phenocrysts of felsitic intrusive porphyries and lavas. In dark traps and basalt lavas it is rare. In the metamorphic rocks it is found in gneisses and is the prominent mineral of the hornblende schists.

Arfvedsonite occurs in nephelite syenites and in rare porphyries.

Uralite is a fibrous or fine needle-like, columnar hornblende, secondary after pyroxene, and, as mentioned under that mineral, produced from it by metamorphic processes. Instances have been found where the outward crystal form of the pyroxene is retained but the substance composing it is this hornblende in parallel bundles of needle-like prisms. Generally it is in aggregates, which may be very fine and felt-like, lying in the plane of schistosity. It is especially likely to occur when basic, pyroxenic igneous rocks have been subjected to dynamic changes in the Earth's crust attended with squeezing and shearing. It varies in composition from actinolite to common hornblende, depending on the kind of pyroxene from which it was derived. It is clear that it cannot be a simple rearrangement of the pyroxene molecule since the latter has twice as much calcium as the hornblende and is lacking in the necessary water or fluorine. Calcium is separated out during the alteration of pyroxene to hornblende to form a carbonate (calcite) or some other mineral, and the presence of water, often containing other substances in solution, is a necessary aid to the dynamic processes of pressure and shearing which, by setting up chemical activity, produce this mineral.

In this connection the reader should consult what is said under metamorphism and the hornblende schists.

Determination. Amphibole may be confused in megascopic work with pyroxene, tourmaline, and epidote. To distinguish it from tourmaline and epidote, use may be made of the various physical properties mentioned under the determination of pyroxene; the good cleavage separates it at once from tourmaline. To distinguish amphibole from pyroxene is much more difficult, owing to the fact that these two minerals have similar chemical compositions and physical properties. The following points will be found of service in this connection. If the mineral appears in tolerably distinct crystals the form should be carefully studied, especially the outline of the section of the prism, which can often be observed on a fractured surface of the rock, and comparison made with Figs. 23 and 28.

In case the crystal form is imperfect or wanting, the angle at which the cleavage surfaces meet should, if possible, be carefully studied, as this is a fundamental character, the cleavage prism, as already described, being nearly square in pyroxene and highly oblique in amphibole. Further, the perfection of the cleavage in amphibole and the bright glittering surfaces it yields furnish indications not commonly seen in pyroxene, the cleavage of which is only fairly good. Amphibole also tends to occur in needles or long-bladed prisms; pyroxene is commonly in short prismoids or grains. Before the blowpipe, amphibole, on account of the combined water (hydroxyl), is more likely to intumesce than pyroxene (arfvedsonite from ægirite), but this cannot be relied on as a general definite test. If fluorine is obtained by a qualitative test this is also indicative of amphibole, but many amphiboles do not contain this element and it is not a method which is ordinarily in one's power to use. Finally, it is often impossible, especially in fine-grained igneous rocks, to tell by purely megascopic means whether the dark ferromagnesian mineral present is hornblende or pyroxene or, as often happens, a mixture of both. Only in a thin section under the microscope can this be certainly determined. This is a limitation imposed by the megascopic method for the study and determination of rocks and rock-minerals.

Olivine

Here

Form. Olivine crystallizes in the orthorhombic system; the crystals are rather complex, as illustrated by a common form shown in Fig. 29. The form is not, however, a matter of importance, as the mineral very rarely shows well-developed crystals in rocks but occurs in grains or small, formless masses composed of grains.

General Properties. There is a cleavage parallel to the face *b* but this is a poor and not a noticeable property in rock grains. The fracture is conchoidal. The color is green, generally of a medium shade and varying from olive-green to a yellow-green; a bottle-green is very common. Olivine is often transparent, varying to translucent, but becomes brown to dark red on oxidation of the iron, and more or less opaque; this is frequently noticed in lavas which have been exposed to the action of steam. Luster vitreous; streak white to yellowish. Hardness 6.5 to 7.0. Specific gravity varies with the iron content from 3.3 to 3.5.

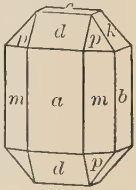

Fig. 29

Chemical Composition. Olivine is composed of magnesium orthosilicate, Mg_2SiO_4, and ferrous orthosilicate, Fe_2SiO_4, which mingle isomorphously in all proportions. The nearly pure magnesium compound is called *forsterite*, the nearly pure iron compound *fayalite;* these occur in rocks but are rare. Much more common are variable mixtures of the two, which make common olivine, or chrysolite, as it is often called. These variations may be seen in the following table of analyses.

	SiO_2	MgO	FeO	XyO*	Total
I....................	41.8	56.2	1.1	0.7	99.8
II...................	39.9	49.2	10.5	...	99.6
III..................	37.2	39.7	22.5	...	99.4
IV...................	41.9	28.5	29.2	...	99.6
V....................	33.6	16.7	44.4	5.0	99.7
VI...................	30.1	...	68.2	1.5	99.8

* XyO = small quantities of other oxides, chiefly MnO.

I, Forsterite, Monte Somma, Italy; II, Olivine, Mt. Vesuvius, Italy; III, Olivine, Montarville, Canada; IV, Olivine, Hochbohl, Germany; V, Hortonolite, Monroe, Orange Co., N. Y.; VI, Fayalite, Rockport, Mass.

Blowpipe and Chemical Characters. Before the blowpipe, olivine is nearly infusible. Varieties very rich in iron fuse and yield magnetic globules; these varieties are likely to turn red on heating. The powdered mineral dissolves in hydrochloric or nitric acid, yielding gelatinous silica on evaporation. The solution may be tested for iron and magnesium as directed under mineral tests.

Alteration. When this takes place through oxidation of the iron, the mineral turns reddish or brownish, and eventually a mass of limonite replaces it, accompanied by carbonates and some form of silica. The rusty iron product is the most noticeable result of the process.

A most important mode of alteration is that by which the olivine becomes converted into serpentine. It is more fully discussed under the head of serpentine. Other substances, such as carbonate of magnesium, magnetite, free silica, etc., are also likely to occur as by-products in the process. Other kinds of alteration of olivine are known but are of less importance.

Occurrence. Olivine is a highly characteristic mineral of igneous rocks, especially the ferromagnesian ones. It so rarely occurs in those composed chiefly of alkalic feldspars — in the granite-syenite rocks, feldspathic porphyries, and felsite lavas — that for practical purposes it need not be sought in them. Anorthosite is the only feldspathic rock in which it may become of importance. Thus its true home is in the gabbros, peridotites, and basaltic lavas. In the basalts it usually occurs in bottle-green grains; in the gabbros and peridotites it is sometimes darkened by inclusions. It also forms masses of igneous rock known as dunite which consist almost wholly of olivine. Fine transparent crystals of olivine from basaltic lavas are frequently cut for gems, commonly called peridotes. The mineral is also often found in meteorites.

Olivine also occurs in metamorphic rocks, in crystalline limestones of dolomitic character, and in other rocks found in such associations, composed of varying quantities of other magnesian (and calcic) silicates, such as amphibole, pyroxene, and talc. Its origin may be ascribed to a reaction between the magnesium carbonate of the dolomite and quartz sand or silica-bearing solutions.

$$2\,MgCO_3 + SiO_2 = Mg_2SiO_4 + 2\,CO_2.$$

But in many such occurrences in the crystalline schists, where it is mixed more or less with other silicate minerals, its presence is probably due to the fact that the masses containing it were originally of igneous origin, rather than metamorphosed sedimentary beds.

Determination. The appearance, associations, and characters described above are usually sufficient to identify the mineral readily. It may be confused with greenish, more or less transparent grains of pyroxene, but the lack of pronounced cleavage, the superior hardness, and easy gelatinization in acid enable one to distinguish it from that mineral.

Garnet

Form. Garnets crystallize in the isometric system in the simple form of the rhombic dodecahedron shown in Fig. 30 or in the trapezohedron shown in Fig. 31. Sometimes they show these forms well developed and are then excellent crystals, which may be more complicated by bevellings or truncations of the edges of the dodecahedron. Very commonly, however, the faces are not well developed and the garnet then appears as a spherical mass or grain.

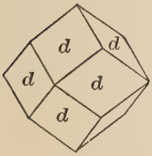

Fig. 30

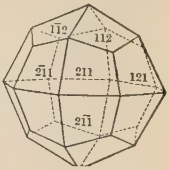

Fig. 31

Cleavage and Fracture. The cleavage is generally poor and not a prominent feature; sometimes, in garnets occurring in sheared rocks, a parting may be seen which suggests a lamellar structure. The fracture is uneven. The mineral is very brittle, but some rocks composed largely of massive garnet are very tough.

Hardness and Specific Gravity. The hardness varies from 6.5 to 7.5; the specific gravity, from 3.55 in grossularite to 4.2 in almandite.

Color, Luster, and Streak. The color depends upon the composition; *grossularite* is sometimes white but usually shows pale tones of green, pink, or yellow, sometimes yellowish or reddish-brown to brown; *pyrope* is deep red to black; *almandite* and most common garnet is deep red to brownish-red; *melanite* is black. The streak is light-colored, and not important. The luster is glassy, sometimes rather resinous. The light-colored garnets are transparent to translucent, the darker ones translucent or opaque.

Chemical Composition. Garnets are orthosilicates of the general formula $\ddot{R}_3\dddot{R}_2(SiO_4)_3$, in which the radical $\ddot{R}$ may be calcium, magnesium, ferrous iron, and other bivalent metals, while $\dddot{R}$ may be aluminum, ferric iron, or chromium, trivalent elements. There is therefore opportunity for a number of combinations which are isomorphous. The garnets of most importance as rock minerals are *grossularite,* $Ca_3Al_2(SiO_4)_3$, *pyrope,* $Mg_3Al_2(SiO_4)_3$, *almandite,* $\ddot{F}e_3Al_2(SiO_4)_3$, and *andradite,* $Ca_3\dddot{F}e_2(SiO_4)_3$. These compounds, however, rarely, if ever, occur pure; generally there are variable amounts of the other molecules present and the mineral is named from the one predominating. *Common garnet* is chiefly *almandite* with more or less admixture of the other molecules. *Melanite,* the black garnet found in some rocks, consists chiefly of the andradite molecule. These facts are illustrated in the following analyses of typical specimens.

	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	XyO	Total
I........	39.8	22.1	1.1	...	0.7	36.3	...	100.0
II.......	40.4	19.7	4.0	6.9	20.8	5.8	2.6	100.2
III......	39.3	21.7	...	30.8	5.3	2.0	1.5	100.6
IV	35.9	19.2	4.9	29.5	3.7	2.4	4.8	100.4
V	35.7	0.1	30.0	1.2	0.1	32.3	0.9	100.3

I, Grossularite, Hull, Ontario. II, Pyrope, Krems, Bohemia, XyO = Cr_2O_3. III, Almandite, Fort Wrangell, Alaska, XyO = MnO. IV, Common Garnet (mostly almandite), Shimerville, Penn., XyO = MnO. V, Andradite, Sisersk, Ural Mts.

Blowpipe and Chemical Characters. The garnets fuse readily before the blowpipe, and in the reducing flame those containing much iron become magnetic. After fusion and grinding of the bead to powder, they dissolve in hydrochloric acid and gelatinize on boiling. They are slightly attacked by acids, andradite quite strongly. They give little or no water by heating in closed glass tube. They are decomposed by fusion with sodium carbonate.

Alteration. Garnets are resistant to weathering, but those containing iron may alter into rusty spots of limonite and other products of weathering.

Occurrence. Common *garnet* is widely distributed as an accessory component of metamorphic and of some igneous rocks. Its most striking occurrence is in schists, especially in many mica schists, though it is also found in other kinds, in many hornblende schists and in gneisses, for example. It frequently occurs in ferromagnesian igneous rocks that have been squeezed and sheared. It is sometimes seen in granite-pegmatites, rarely in granite itself, in occasional scattered crystals. *Pyrope*, which chiefly furnishes the garnet used as a jewel, is an accessory component of some peridotites and the serpentines derived from them. *Grossularite* occurs especially in recrystallized limestone beds, as a result of either contact or regional metamorphism. *Melanite* occurs mostly in certain igneous rocks and is not an important megascopic mineral. *Andradite* occurs in enormous masses in certain ores of contact-metamorphic origin.

Determination. The crystal form of garnets, the appearance, color, and hardness are generally sufficient to enable one to recognize them easily, and in case of doubt the blowpipe tests will furnish sufficient confirmation.

Epidote

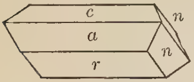

Fig. 32

Form. Epidote crystallizes in the monoclinic system, the simplest form being that shown in Fig. 32; the crystals tend to be more complex with other faces. Well-developed crystals usually occur only in druses in seams and cavities and the form is therefore not generally a character which can be of much use in megascopic rock determination. Epidote is commonly seen in bladed prisms extended in the direction of the edge *ac* and sometimes passing into slender, needle-like forms. It is often found in bundles or aggregates of prisms or needles. Terminations of prisms are often rounded. It also occurs in spherical and angular grains and in aggregates of such grains.

General Properties. The *cleavage* is perfect in the direction parallel to *c*, parallel to *a* imperfect. Fracture uneven. Brittle. *Hardness* is 6 to 7. Specific gravity is 3.3 to 3.5. The *color* in general is green, usually a peculiar yellowish green, varying from pistachio-green to olive, sometimes very dark green, rarely brownish. Luster vitreous. Streak whitish. Translucent to opaque.

Chemical Composition. Epidote is really the name of a group of complex silicates, salts of orthosilicic acid, the hydrogen atoms of which are replaced by calcium and by a set of isomorphous radicals composed of variable amounts of aluminum, ferric iron, and sometimes other elements, and of hydroxyl. Of these, only common rock-making epidote is described in this section and it may be represented as consisting of mixtures of $Ca_2(AlOH)Al_2(SiO_4)_3$ and $Ca_2(\dddot{Fe}OH)\dddot{Fe}_2(SiO_4)_3$. The composition may be seen in these two representative analyses.

	SiO_2	Al_2O_3	Fe_2O_3	FeO	CaO	H_2O	XyO	Total
I........	37.8	22.6	14.0	0.9	23.3	2.1	...	100.7
II.......	37.0	25.8	10.0	1.3	21.9	3.0	1.0	100.0

I, Untersulzbach, Pinzgau. II, Macon Co., North Carolina, XyO = MnO and MgO = 0.5 each.

Blowpipe and Chemical Characters. Before the blowpipe, epidote fuses easily with intumescence to a black, slaggy mass. Intense heating in the closed glass tube causes the finely powdered mineral to give off water. Epidote is only slightly acted on by hydrochloric acid but after fusion dissolves and gelatinizes. It reacts with fluxes for iron and decomposes on fusion with sodium carbonate.

Occurrence. Epidote is characteristic as a product of alteration of other minerals. It appears through the weathering of igneous rocks that contain large amounts of calcium, iron, and aluminum silicates and is then usually associated with chlorite. When igneous rocks of this character also suffer regional metamorphism, epidote is likely to form. The occurrences in which it appears most notable from the megascopic viewpoint are those in which mixed sedimentary beds (impure limestones) containing calcareous matter, with sand, clay, and limonite are subjected either to general or contact metamorphism. Then epidote is often formed, usually in company with other silicates, but sometimes so extensively as to form masses that consist almost entirely of this mineral.

Determination. The peculiar yellow-green color, superior hardness, perfect cleavage in one direction only, and the blowpipe characters described above generally suffice to distinguish epidote from hornblende, pyroxene, and possibly tourmaline, with which it might be confused. The hardness distinguishes it at once from some varieties of serpentine which resemble it in color. This may be confirmed by a chemical test showing the absence of magnesium as described in the section on mineral testing.

Zoisite. This is a mineral which has nearly the same chemical composition as epidote and is closely related to it. It consists almost wholly of the calcium-aluminum molecule previously mentioned and contains little or no ferric iron. It is orthorhombic in crystallization but in the crystals occurring in rocks this can generally be told only by optical methods: zoisite occurs in aggregated blades or prisms, parallel or divergent or in grains and masses. Its color is usually gray of varying shades. From epidotes lacking in iron it can be told only by crystallographic investigations.

Vesuvianite

Vesuvianite is a tetragonal mineral which generally crystallizes in short thick square prisms terminated by a pyramid, commonly cut off by a basal plane, as illustrated in Fig. 33. It also occurs in lumps or grains. The *cleavage* is poor, being best in the direction parallel to the prism faces *m*; fracture is uneven. The *color* generally varies from green to brown. The *luster* is vitreous. *Hardness* is 6.5; *specific gravity*, about 3.4. The mineral is subtransparent to subtranslucent. In *chemical composition* vesuvianite is a basic calcium-aluminum silicate containing hydroxyl and fluorine, but small amounts of ferric iron and magnesium are generally present. Some varieties, as that from Brooks Mountain, Alaska, contain also boron. The formula has been written $H_4Ca_{12}(AlFe)_6Si_{10}O_{43}$ but this is probably not correct. Before the blowpipe it fuses readily with intumescence to a greenish or brownish glass, which gelatinizes with hydrochloric acid. The fresh mineral is slightly soluble in hydrochloric acid.

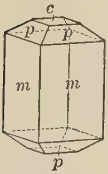

Fig. 33

As a rock-forming mineral, vesuvianite characteristically occurs in limestones that have become crystalline through the contact action of igneous rocks, and its formation is evidently conditioned by the pneumatolytic emanations of water and fluorine from the igneous magmas. In these occurrences it is commonly associated with garnet, pyroxene, tourmaline, chondrodite, and other contact minerals.

Vesuvianite may be confused with garnet, pyroxene, epidote, or hornblende, but the study of its crystal form, its other physical characters, and its behavior before the blowpipe will generally serve to distinguish it from them.

Staurolite

Form. Staurolite is orthorhombic in crystallization and usually in distinct crystals of the form shown in Fig. 34. They are often stout and thick, sometimes long and more slender but not strikingly so. The angle of the faces *m* on *m* is 50° 40′. They are terminated by flat bases *c*, though it often happens that these cannot be seen in the rock. Staurolite commonly forms compound twinned crystals as shown in Figs. 35, 36. From this fact its name is derived, from the Greek, meaning a cross.

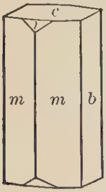

Fig. 34

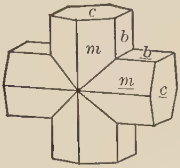

Fig. 35

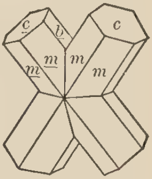

Fig. 36

Physical Properties. The mineral has a moderate but distinct cleavage parallel to the face *b*; the fracture is subconchoidal. The color varies from a dark reddish or yellowish brown to almost black; the light transmitted through thin splinters appears almost blood-red. The streak is white to gray. The hardness is 7 to 7.5, the specific gravity 3.75.

Chemical Composition. The formula is rather complex, $(AlO)_4(AlOH)\ddot{Fe}(SiO_4)_2$; the aluminum may be partly replaced by ferric iron and the ferrous iron by magnesium, as seen in the included analysis of a crystal from Franklin, North Carolina. The percentage of silica is very low;

SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	H_2O		Total
27.91	52.92	6.87	7.80	3.28	1.59	=	100.37

staurolite is one of the rock-forming silicates containing the least silica, and this fact, with the high alumina, is significant of its place and mode of origin — in metamorphosed clay rocks.

Blowpipe and Chemical Characters. Staurolite is practically infusible before the blowpipe. It is almost insoluble in acids. It may be fused with carbonate of soda and the resulting fusion, after solution in hydrochloric acid, may be tested for aluminum, iron, and magnesium. It is easily recognized by its color, crystal form, hardness, method of twinning, and mode of occurrence.

Occurrence. Staurolite occurs in the metamorphic rocks; it is a highly characteristic mineral of the crystalline schists. It is found in mica schists, in certain slates, and sometimes in gneiss. Frequently it is associated with dark red garnets in these rocks.

Andalusite

Andalusite is orthorhombic in crystallization and is usually seen in rough prisms, nearly square in cross section. Sometimes the prisms are collected in radiated groups. The *cleavage* parallel to the prism is good — in other directions poor. *Fracture* is uneven to subconchoidal. The normal *color* is white to pink or red to brown, but the mineral is very likely to contain impurities, especially particles of carbonaceous matter, which may color it dark or even black. Often these are arranged in a symmetrical manner in the crystal so that the cross section, when it is broken or cut, displays a definite pattern, such as a black cross in a white square. This may help to identify the mineral. It is usually *subtranslucent* in thin splinters. *Brittle.* *Hardness,* 7.5. *Specific gravity,* 3.2. *Streak,* whitish. The *chemical composition* is $Al_2SiO_5 = Al_2O_3 . SiO_2$. It is *insoluble* in acids but decomposed by fusion with carbonate of soda. Before the blowpipe it is *infusible;* after moistening with cobalt nitrate solution it turns a blue color upon intense ignition (as do also cyanite and some other aluminum minerals).

Andalusite is a mineral especially characteristic of the contact zones of igneous rocks, such as granite. It is produced by the alteration of clay slates and shales as described on a later page. Sometimes, though rarely, it is found in granite.

Cyanite

Cyanite, or kyanite, usually occurs in long bladed crystals which rarely show distinct end faces, or in coarsely bladed columnar masses. It is triclinic. It has one very perfect cleavage (parallel to the face *a*) and another less so (parallel to *b*); the angle between these is about 74 degrees.

The color is white to pure blue; sometimes the center of the blade is blue with white margins; rarely gray, green to black. Streak, whitish. Transparent to translucent. Luster, vitreous to pearly. Hardness varies in different directions from 5 to 7; least on face *a* (best cleavage), greatest on face *b* (second cleavage). Specific gravity, 3.56 to 3.67. Chemical composition, Al_2SiO_5, and other chemical and blowpipe properties similar to those of andalusite, mentioned above.

Cyanite is a mineral characteristically developed in regions subjected to intense regional metamorphism. It occurs in gneisses and in mica schists. In the latter the mica is sometimes muscovite and sometimes the soda-bearing variety, paragonite. Cyanite is often associated with garnet, sometimes with staurolite or corundum. It alters to talc and steatite.

Cyanite is easily distinguished from other minerals, especially andalusite, which has the same chemical composition, by its form, color, variable hardness, specific gravity, and other properties.

Sillimanite. With andalusite and cyanite may be mentioned sillimanite, a mineral which has a chemical composition identical with theirs, but which is separated mineralogically because it has a different crystal form as shown by its angles. It is of importance chiefly in microscopical studies, but it may sometimes be seen with the eye or lens, mostly in gneisses or quartzites, as slender white or light-colored, four-sided prisms, or radiated aggregates of them forming brushes. Its blowpipe and other chemical characters are like those described for andalusite and cyanite.

Tourmaline

Tourmaline is a mineral of which there are a number of varieties based on the color, which in turn depends on the chemical composition. The chief ones are black, green, brown, and red, but of these the black variety known also as *schorl* is the only one that is of importance in megascopic petrography.

Form. Tourmaline crystallizes in the rhombohedral division of the hexagonal system. The faces therefore are in threes or multiples of three. A simple form is shown in Fig. 37; the same form, as it appears to an observer looking down upon the upper end, in Fig. 39. It consists of the three-cornered prism *m*, its edges beveled by the prism faces *a* and terminated by the rhombohedron *r*. The crystals, if well developed, tend to be more complicated than this, other faces being present, and if both ends are perfect they have unlike faces. Though sometimes short and thick, the crystals are commonly elongated prisms, often extremely long and thin. Very often also the faces *a* and *m* alternate repeatedly, so that the prism is striated or channeled as shown in Fig. 38 and the outline and appearance from above is that seen in Fig. 40. This spherical triangle cross section is very characteristic of the prisms of rock-making tourmaline. It is rarely found in formless grains or large shapeless masses. The slender prisms and needles are commonly assembled together into bundles, sheaves, and radiate groups. The section of the latter in rocks furnishes the so-called "tourmaline suns."

Fig. 38

General Properties. Tourmaline has no good cleavage and its fracture is rather conchoidal to uneven. It is brittle. The *color* is black, the luster glassy, sometimes dull; streak uncolored, not characteristic. The mineral is opaque. The *hardness* is 7 to 7.5, the specific gravity 3.1 to 3.2. Tourmaline becomes electrified by friction.

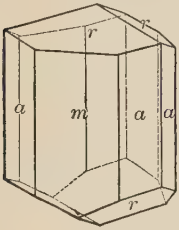

Fig. 37

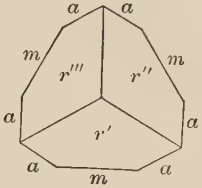

Fig. 39

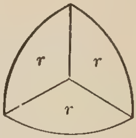

Fig. 40

Chemical Composition. Tourmaline is a very complex silicate of boron and aluminum with hydroxyl and sometimes fluorine and with magnesium, iron, and sometimes alkali metals. It may be said to be a salt of an aluminum-borosilicic acid in which the hydrogens are replaced by iron, magnesium, alkalies, and aluminum in varying amounts. This acid has been formulated as $H_9Al_3(BOH)_2Si_4O_{19}$, and in common black tourmaline the hydrogens are replaced mostly by iron or iron and magnesium, as shown in the analyses here given.

	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	Na_2O	B_2O_3	H_2O	XyO	Total
I...	35.0	34.4	1.1	12.1	1.8	2.0	9.0	3.7	0.6	99.7
II..	35.6	25.3	0.4	8.2	11.1	1.5	10.1	3.3	4.3	99.8

I, Paris, Maine. II, Pierrepont, New York. XyO = small quantities of other oxides, etc.

Blowpipe and Chemical Characters. Tourmaline fuses with difficulty before the blowpipe with swelling and bubbling. When mixed with powdered fluor spar and bisulphate of potassium, it momentarily colors the flame a fine green, thus showing the presence of boron. It is decomposed on fusion with sodium carbonate. It is not acted on by acids but after fusion gelatinizes in hydrochloric acid.

Occurrence. Tourmaline is not a common megascopic component of rocks, but it is of interest and importance because it is perhaps the most common and typical mineral that is produced in the pneumatolytic or fumarole stage of igneous rock formation as described in another place. This is indicated by the boron, hydroxyl, and fluorine which it contains. Thus it is one of the most common and characteristic accessory minerals found in the pegmatite dikes associated with intrusions of granites; its presence in granite indicates, as a rule, nearness to the contact, and in the rocks that have suffered contact metamorphism it is very likely to appear. In this way it is not infrequently found associated with certain ore deposits. It appears at times also in gneisses, in schists, and in crystalline limestones of the metamorphic rocks and its occurrence in these indicates that the metamorphism has been induced in part by the contact action of igneous masses giving off water vapors and other volatile substances. The beautiful red and green transparent tourmalines which are valued as gem material occur in pegmatite dikes of granite, often associated with the common black variety. The red is usually found with lepidolite — the lithium mica.

Determination. The black color, crystalline form, and mode of occurrence of common tourmaline are usually sufficient to identify it. From black hornblende it is easily distinguished by its lack of good cleavage, superior hardness, and the shape of the cross section of the prism; and this determination can be made certain by the blowpipe test for boron.

Topaz

Topaz crystallizes in the orthorhombic system and the *form* in which it is generally seen is in pointed prisms, as illustrated in Fig. 41. There is a very perfect *cleavage* parallel to the base c, at right angles to the prism: the *fracture* is uneven. The mineral is very hard = 8, and brittle. The specific gravity is about 3.5. In color it is, while generally transparent, often colorless, sometimes yellow to brown-yellow, sometimes white and translucent. The *luster* is vitreous. The *chemical composition* as established by Penfield is $(AlF)_2SiO_4$, in which the fluorine may be replaced in part by hydroxyl $(-OH)$. Before the blowpipe it is infusible. If topaz is fused in a closed tube with previously fused and powdered phosphorus salt, hydrofluoric acid will be given off and will etch the glass and deposit a ring of silica on the colder upper walls of the tube. If the pulverized mineral be moistened with cobalt nitrate solution and intensely heated before the blowpipe on charcoal it assumes a fine blue color, thus showing the presence of aluminum.

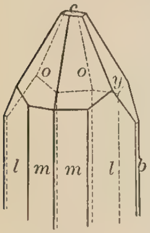

Fig. 41

Topaz, while not a common or important rock-forming mineral, is a very interesting one as it is particularly characteristic of the pneumatolytic stage in the formation of igneous rocks.

Thus it is found in crystals in the miarolitic cavities of granites where the vapors have collected and in the same way in felsite lavas (especially in rhyolite). It is also found in pegmatite dikes and in the cracks and crevices of the surrounding rocks which have served as channel ways for the escape of gases as explained under the description of pegmatite dikes and of contact metamorphism. It is generally associated in these occurrences with quartz, mica, tourmaline, and sometimes with cassiterite, tin ore.

The form, color, cleavage, and great hardness of topaz, together with its mode of occurrence, serve to distinguish it readily from other minerals, and the determination may be confirmed by the chemical tests mentioned above.

Chondrodite

Chondrodite is really one of a small group of minerals — chondrodite, humite, clinohumite, etc. — which are so closely allied in all of their general properties that for practical megascopic rock work they are indistinguishable and may all be comprised under this heading. While the mineral is monoclinic it rarely shows, as a rock component, any definite crystal form which is of value in determining it, but appears as embedded grains and lumps. The *cleavage* is not marked but is sometimes distinct in one direction. Brittle; fracture subconchoidal. The *color* is yellow, honey yellow to reddish yellow, to brown red. *Luster* vitreous. *Hardness* 6 to 6.5. *Specific gravity* 3.1 to 3.2. In *chemical composition* the mineral is closely allied to olivine but differs in containing fluorine or hydroxyl or both, as may be seen from the following formulas deduced by Penfield.

$$
\begin{aligned}
\text{Olivine} &= Mg_2SiO_4.\\
\text{Chondrodite} &= Mg_3[Mg(F,OH)]_2(SiO_4)_2.\\
\text{Humite} &= Mg_5[Mg(F,OH)]_2(SiO_4)_3.\\
\text{Clinohumite} &= Mg_7[Mg(F,OH)]_2(SiO_4)_4.
\end{aligned}
$$

As in olivine, part of the magnesium is usually replaced by some ferrous iron. The powdered mineral is slowly dissolved by hydrochloric acid, yielding gelatinous silica. The solution, evaporated to dryness, then moistened with acid and taken up in water, after the silica is filtered off yields tests for iron with excess of ammonia, and after separation of the iron by filtering, for magnesium with sodium phosphate solution. From olivine it may be distinguished by a test for fluorine as described under topaz. Before the blowpipe it is nearly infusible.

The characteristic mode of occurrence of chondrodite is in limestone, especially dolomite, that has been subjected to contact action of igneous rocks. In this it forms yellowish or reddish embedded grains or lumps usually associated with other contact minerals such as pyroxene, vesuvianite, magnetite, spinel, phlogopite, etc. The presence of the hydroxyl and fluorine shows its derivation by pneumatolytic processes.

The appearance, color, mode of occurrence, and associations are usually sufficient to identify the mineral, and these may be confirmed by the chemical tests mentioned.

b. Oxides, etc.

The list of important rock-making oxides includes, first, silica, SiO_2, and then corundum, Al_2O_3. Then come the oxides of iron which are of importance as nearly ubiquitous accessory minerals in rocks and therefore have a wide distribution. For this reason two other minerals, not oxides — pyrite, the sulphide of iron, and apatite, the phosphate of calcium — are also here included. Limonite, the hydrated oxide of iron, which is always secondary, is placed with the other iron ores for the sake of convenience.

Quartz

Form. Quartz crystallizes in the hexagonal system, the ordinary form being an hexagonal prism terminated by a six-sided pyramid. This form, which is the common one for the crystals of veins and is illustrated in Fig. 42, is not often seen in the quartzes of rocks, except in igneous rocks that possess miarolitic or drusy cavities; into them the rock-making quartzes project with free ends which show crystal form. The large crystals seen in pegmatite veins and which sometimes attain huge dimensions are only a manifestation of the same thing on a larger scale, as explained under the pegmatite formation of igneous rocks. In porphyries where quartz may have crystallized free as phenocrysts, it tends to take the form shown in Fig. 43; the two pyramids are present and the prism is very short or generally wanting. Since the crystals are usually poorly developed, with rough faces, they appear as spherical objects, like shot or peas, embedded in the rock, with round cross sections where broken across on a fracture face. In general, quartz has no definite form in rocks, especially in igneous ones like granite, where,

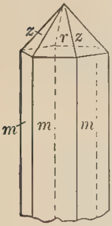

Fig. 42

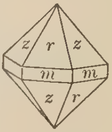

Fig. 43

as it is usually the last substance to crystallize, its shape is conditioned by the other minerals which have already formed. In granites, therefore, it commonly appears in small shapeless lumps and masses, but in some of the fine-textured varieties the quartz tends to appear in granules like those composing lump sugar. In pegmatite dikes it appears on fracture surfaces in curious script-like figures intergrown with feldspar, forming the substance known as graphic granite.

Cleavage and Fracture. The cleavage of quartz is so poor that for practical petrographic purposes it may be regarded as not possessing any. It has commonly a good conchoidal fracture, which is a great help in distinguishing it in granitic rocks, but in some massive forms it is uneven and splintery. The mineral is brittle to tough.

Color and Luster. Rock-making quartz varies in color from white through shades of gray and dark smoky gray or brown to black. The gray and smoky tones are most common in igneous rocks and the white color in the sedimentary and metamorphic ones, but there is no absolute rule about this. The black color is rare and mostly confined to igneous rocks; sometimes in them it has a strong bluish tone. The colorless, limpid quartz, so characteristic of the crystals found in veins and geodes and deposited by solution, is rare as a rock-making component but sometimes occurs, as in certain very fresh lavas. The mineral may also at times possess an exotic color given it by some substance acting as a pigment; thus it may be red from included ferric oxide dust or green from scales of chlorite, and in the sedimentary and metamorphic rocks, such as quartzite, it may be very dark from included organic matter or charcoal-like substance.

The luster varies from glassy to oily or greasy. The *streak* is white or very pale colored and not a prominent character. *Hardness* is 7. Quartz scratches feldspar and glass but is not scratched by the knife. *Specific gravity* = 2.65.

Composition. Quartz is pure silica, SiO_2. This is the composition of the crystallized common rock-making quartz, but certain massive varieties of silica, which are not crystallized or not apparently so, and are of common occurrence and sometimes take part in forming rocks, such as jasper, opal, chert, etc., contain in addition more or less combined water, while impurities like clay, oxides of iron, etc., are usually present and give them distinctive colors.

Blowpipe and Chemical Characters. Quartz is infusible before the blowpipe — varieties that are dark from organic matter whiten but do not fuse. Fused with carbonate of soda, it dissolves with effervescence of CO_2 gas. In the sodium metaphosphate bead a fragment floats without dissolving. It is insoluble in acids except hydrofluoric, HF.

Occurrence. Quartz is one of the commonest of all minerals, and is universally distributed, occurring in igneous, sedimentary, and metamorphic rocks alike. Not only does it form rocks in company with other minerals, chiefly feldspar, but in pure sandstones and quartzites it may be the only one present in the rock mass. It is indeed so common that, except in the limestones and marbles and dark, heavy igneous rocks like dolerite and basalt, its presence in rocks should at least always be suspected.

Determination. The hardness of quartz, its lack of cleavage, its conchoidal fracture, and glassy luster are characters which help to distinguish it, especially from the feldspars with which it is so often associated. The gray and smoky color it often has in granites and other igneous rocks helps in the same way. It may be confused with nephelite but this mineral is readily soluble in acids with gelatinization and, moreover, is very rare. These characters, with the blowpipe and chemical ones mentioned above, will readily confirm the determination of quartz.

Opal, Jasper, Flint, Chalcedony, etc. Silica, in addition to forming the crystallized anhydrous mineral quartz, occurs in non-crystalline, amorphous masses which contain varying amounts of water. According as the color, structure, and other properties vary, a great number of different varieties are produced which have received particular names. For a description of them the larger manuals of mineralogy should be consulted. They seem to have been formed, in large part at least, by deposition from liquids containing colloidal silica, which has been deposited in an amorphous, more or less hydrated condition instead of as crystalline quartz. The resultant mineral is known as opal. By dehydration and crystallization, opal may change to chalcedony. Some of these minerals are mixtures of quartz particles or fibers mixed with amorphous material. The colloidal form of silica is illustrated by the gelatinous product obtained when a silicate like nephelite is dissolved in an acid and the resulting solution evaporated. Opal is also formed in nature as a secretion from water by various living organisms, such as diatoms, sponges, and others.

Amorphous silica is not a rock component of any megascopic importance in igneous or metamorphic rocks, but in the sedimentary ones it forms accompanying masses and sometimes beds which, although not of wide general importance, may be of considerable local interest and value. These are further noticed in their appropriate places. It may also act as a cementing substance of the grains of some rocks.

Corundum

Form. The crystallization is hexagonal and the form assumed is either a thick six-sided prism, often swelling out in the middle into barrel-like shape, or is a six-sided table; corundum also occurs commonly in grains or shapeless lumps. The thick and barrel forms are most common when it occurs in massive rocks like the syenites, and they are associated with the grains and lumps. Sometimes on parting faces a multiple twinning, resembling that illustrated as occurring on feldspars, may be observed; it is produced, however, by another method.

Cleavage. Corundum does not have a good cleavage but possesses a parting that appears like perfect cleavage parallel to the base of the prism and also in three other directions at an angle to it (parallel to the unit rhombohedron). In large pieces these partings or pseudo-cleavages may appear nearly at right angles, and the mineral has a laminated structure.

Color, Luster, and Hardness. Rock-making corundum is usually dark gray to bluish gray or smoky. It is very rarely blue, forming the variety sapphire, while the red variety or ruby is excessively rare. The luster is adamantine to vitreous, sometimes dull and greasy in rock grains. Corundum is translucent to opaque. It is the hardest of rock minerals = 9.

It is brittle, though sometimes very tough. Specific gravity = 4.

Blowpipe and Chemical Characters. Before the blowpipe it is infusible. The powder, moistened with cobalt solution and intensely ignited, turns bright blue, showing that aluminum is present. It is insoluble in acids. Its composition is pure alumina, Al_2O_3.

Occurrence. In recent years corundum has been recognized as an important primary mineral in the igneous rocks of a number of regions, in syenites in Canada, Montana, and India, in peridotites in North and South Carolina and Alabama, and in other igneous rocks in the Urals and in California. An unrecorded occurrence is in syenite in Orange County, New York State. Many more such will doubtless be discovered. The variety sapphire has been found in basaltic rocks in Montana, the Rhine district, and elsewhere. Corundum also occurs in the contact zone of igneous rocks, where it is usually in thin tabular crystals. It also occurs in metamorphic rocks, sometimes in thick beds of the variety called emery. Probably in many of these occurrences it antedates the period of metamorphism and is of igneous origin.

Determination. The crystal form, when present, and the color indicate the presence of this mineral, which is readily confirmed by a test of its hardness, since it cannot be scratched by another of the rock minerals. These tests may be confirmed by the other described properties.

The Iron Ores

The term ore is commonly applied to the oxides, sulphides, and carbonates of the heavy metals as the sources from which they are obtained in commercial quantities. Of these minerals the only ones that, by reason of their wide distribution and common occurrence as components of rocks, may be considered of general importance from the petrological standpoint are the oxides and sulphides of iron. Even these play only a subordinate rôle in rock-making and are considered as accessory minerals, except where they have been concentrated by geologic processes into considerable masses. They are considered accessory minerals because, in one form or another, they are found scattered in small quantities through most rocks and in each of the three great classes of rocks and do not therefore have the same importance and value in classification as those minerals, such as feldspars and pyroxenes, which occur in large and varying amounts. They are mentioned here because they are the most common of accessory rock-minerals and are of importance in other ways as well. They include *magnetite*, *ilmenite*, *hematite*, *limonite*, and *pyrite*. There are other oxides and sulphides of iron but they are relatively of small petrographic importance.

Magnetite

Form. Magnetite crystallizes in the isometric system, most commonly in octahedrons, Fig. 44, sometimes in dodecahedrons, Fig. 45, sometimes in a combination of both, Fig. 46. It may occur in distinct crystals in rocks but usually is in small grains the form of which cannot be distinguished. It rarely occurs in larger irregular masses.

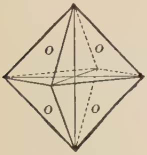

Fig. 44

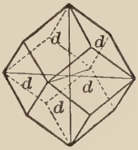

Fig. 45

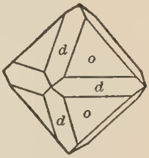

Fig. 46

General Properties. No distinct cleavage but sometimes a parting parallel to the octahedral faces, resembling cleavage. Fracture, uneven. Brittle. Color, dark gray to iron-black; opaque; luster, metallic, fine to dull. Often resembles bits of iron or steel in the rocks. Streak, black. Magnetic. Hardness, 5.5 to 6.5. Specific gravity, 5.2. The chemical composition is $Fe_3O_4 = \ddot{Fe}O \,.\, \dddot{Fe}_2O_3$, or $FeO = 31.0$ per cent,

$Fe_2O_3 = 69.0$. It is difficultly fusible before the blowpipe and in the oxidizing flame becomes non-magnetic: slowly soluble in hydrochloric acid.

Occurrence. Magnetite is one of the most widely distributed of all minerals. It is found in all kinds of igneous rocks, usually in small grains, but sometimes segregated into considerable masses. It occurs also in rocks produced by contact metamorphism and in the crystalline schists, sometimes in large bodies. It is uncommon in the unmetamorphosed sedimentary rocks. It is one of the most important ores of iron.

Determination. The appearance of magnetite in small dark metallic-looking particles is usually sufficient to distinguish it in the rocks, and this may be confirmed by a test of its hardness, streak, and magnetism, together with the other properties described above. It is not likely to be confused with any other mineral except ilmenite.

Spinels

Magnetite may be regarded as the type of a group of minerals known as the spinels. They have the general chemical composition $\ddot{R}O.\dddot{R}_2O_3$ and crystallize in isometric octahedrons as illustrated in magnetite. In them the RO is either MgO, FeO, MnO, or ZnO or mixtures of them; R_2O_3 is Fe_2O_3, Al_2O_3, or Cr_2O_3 or mixtures of them. True spinel is $MgAl_2O_4$ ($MgO.Al_2O_3$) and when transparent and of good color is sometimes cut as a gem. Hercynite is iron spinel, $FeAl_2O_4$, and chromite is $FeCr_2O_4$, more or less mixed with other spinel molecules. Depending on their composition, the spinels have various colors, black, green, red, and gray. They are extremely hard, 7 to 8, without good cleavage, and are of high luster to pitchy. Some of the spinels are constituents of igneous rocks, especially of those low in silica and rich in iron and magnesia, like peridotite and dunite; others are found in metamorphic rocks, especially those produced by contact metamorphism. They are always only accessory and not important components of the rocks and, except in some contact rocks, are rarely found in crystals sufficiently large to make them of megascopic importance.

Ilmenite

General Properties. Ilmenite crystallizes in the hexagonal system like hematite, but it is so rarely seen in good megascopic crystals in rocks that its crystal form is not a matter of importance. It usually occurs in embedded grains and masses, sometimes in plates of irregular to hexagonal outline. No cleavage; fracture, conchoidal; brittle. Color, iron-black, sometimes with faint reddish to brownish tinge; luster, submetallic; streak, black to brownish-red. Opaque. Hardness, 5 to 6. Specific gravity, 4.5 to 5. Composition, $FeTiO_3 = FeO . TiO_2$. $FeO = 47.3$, $TiO_2 = 52.7$. Is not generally pure, but more or less mixed with hematite, Fe_2O_3, with which it is isomorphous. Before the blowpipe very difficultly fusible; in the reducing flame becomes magnetic. After fusion with sodium carbonate can be dissolved in hydrochloric acid, and the solution, after addition of hydrogen peroxide, becomes yellow, thus showing titanium. Fresh mineral is difficultly soluble in acids; decomposed by fusion with bisulphate of potash. The solutions give reaction for iron with potassium ferricyanide. The test for titanium is the safest method to determine the mineral.

Occurrence. Ilmenite, or titanic iron ore, as it is often called, is a widely spread mineral occurring as a common accessory component in igneous rocks in the same manner as magnetite, which it often accompanies. In the same way it is found in gneisses and schists. Unless the embedded grains are of such size that they can be safely tested it cannot usually be discriminated from that mineral by simple inspection. The most important megascopic occurrences are in the coarser-grained gabbros and anorthosites where the mineral is very common and is, indeed, not infrequently segregated in places into such large beds and masses that it would be a useful ore of iron if some method of profitably smelting it could be discovered.

Hematite

Form. Hematite crystallizes in the rhombohedral division of the hexagonal system but is so rarely in distinct well-formed crystals of observable size as a rock constituent that this is not a matter of practical importance.

It occurs as a rock-mineral in three different forms: as *specular iron ore*, *micaceous hematite*, and *common red hematite*.

In the first it forms masses and plates, the latter sometimes hexagonal in outline. Its color is black to steel-gray with sometimes a faint reddish tone. It is opaque, and has a metallic luster which is sometimes very fine or splendent so that it resembles polished steel or iron; at other times it is rather dull but metallic-looking. Fracture, subconchoidal; no cleavage.

As micaceous hematite it occurs in thin flakes which somewhat resemble mica; often they are so thin as to be translucent and then have a deep red color. The luster is submetallic to metallic, sometimes splendent like that of the specular form. The thin leaves are usually of ragged outlines but sometimes hexagonal.

Common red hematite does not appear crystallized. The mineral is massive, sometimes columnar or granular, often in stalactitic or mammillary forms, and sometimes earthy. It is dull, without metallic luster, opaque, and of a dark red color.

General Properties. The streak of hematite is of a red color, from bright Indian red to brownish red, and furnishes the most convenient method of distinguishing it from magnetite and limonite. Before the blowpipe it is very difficultly fusible except in fine splinters. After being heated in the reducing flame, it is magnetic. It dissolves slowly in hydrochloric acid and the solution gives reactions for iron.

The composition is Fe_2O_3, ferric oxide. The hardness varies from 5.5 to 6.5; specific gravity of the specular variety is 5.2.

Occurrence. Hematite is one of the most widely diffused of minerals. The specular variety is a common accessory component of feldspathic igneous rocks, such as granite. It is also found in the crystalline schists, often in thick beds and masses.

Micaceous hematite occurs in the crystalline schists, in megascopic form, as in itabirite, and also, in minute microscopic scales, is the red coloring matter found in igneous and metamorphic rocks. The red color of many potassium feldspars is due to it and so is that of many slates.

Common red hematite is found in sedimentary and metamorphic rocks in beds and masses, often of great size and forming one of the most valuable ores of iron. It is the interstitial cement of many stratified rocks, such as red sandstones, and as a red pigment in the form of powder it is everywhere distributed in all classes of rocks and in soils, though possibly it may sometimes be replaced by turgite (hydrohematite), $2\ Fe_2O_3 . H_2O$, which often closely resembles it. Earthy red hematite, usually more or less mixed with clay, is called red ocher.

Limonite

Form. Limonite occurs in earthy, formless masses in the rocks, and when found in considerable deposits very frequently exhibits compact stalactitic or mammillary shapes which are sometimes concretionary; sometimes it occurs in earthy beds or deposits.

General Properties. No cleavage. Luster of compact varieties often silky to submetallic, but generally dull and earthy. Color, various shades of brown from very dark to brownish yellow. The surface of the compact stalactitic or mammillary forms often has a varnish-like skin. Opaque. Streak, yellow-brown. The hardness of the compact mineral varies from 5 to 5.5 and the specific gravity from 3.6 to 4.0. The composition is $Fe_2O_3 . H_2O$. $Fe_2O_3 = 89.9$; $H_2O = 10.1 = 100$. The water content of limonite has a wide range, however. Most limonite is essentially an amorphous form of the monohydrate of iron with adsorbed and capillary water. The fibrous crystalline form of the monohydrate is mainly goethite. Difficultly fusible before the blowpipe; becomes magnetic in the reducing flame. Heated in closed glass tube, gives off water. Slowly soluble in hydrochloric acid, the solution giving reactions for iron. The yellow streak is the most convenient means of distinction from hematite.

Occurrence. Limonite occurs in several different ways. In all cases it is strictly a secondary substance formed at the expense of previously existing minerals, by the various agencies of weathering and alteration. In igneous and metamorphic rocks it is frequently seen as small, earthy, yellowish to brownish masses which represent the decay of some previous iron-bearing mineral, such as pyrite, hornblende, etc. Accumulated in beds, as explained under sedimentary rocks, it frequently has the compact form with stalactitic and mammillary or concretionary structure. As bog iron ore it is loose, porous, and earthy. Mixed with more or less clay it forms yellow ocher and is the yellow pigment of many soils and sedimentary rocks.

Pyrite

Form. Pyrite almost invariably occurs in crystals in the rocks, very seldom in grains and masses. It crystallizes in the isometric system. It is frequently seen in cubes or in the twelve-sided form shown in Fig. 47 and called the pyritohedron because this mineral so commonly shows it. Combinations of the two are also very common, as shown in Fig. 48. Very often the cubic faces are striated by fine lines, as seen in Fig. 50, produced by oscillating or repeating combinations of the pyritohedron on the cube faces. The octahedron is less frequent and is likely to be modified by the pyritohedron, combining with it as in Fig. 49. Other more complex forms also occur.

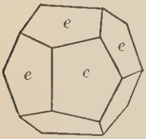

Fig. 47

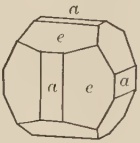

Fig. 48

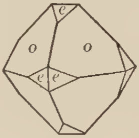

Fig. 49

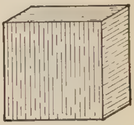

Fig. 50

General Properties. No good cleavage; fracture, conchoidal to uneven. Color, brass yellow; luster, metallic, splendent, duller when tarnished. Opaque. Streak, greenish to brownish black. Hardness, 6 to 6.5; specific gravity, 5.0. Composition, FeS_2; iron = 46.6, sulphur = 53.4 = 100. Easily fusible before the blowpipe, burning and giving off sulphur dioxide gas, and leaving a magnetic globule. In the closed glass tube on heating gives a sublimate of sulphur and leaves a magnetic residue. Insoluble in hydrochloric but decomposes in boiling nitric acid with separation of sulphur.

The color and crystallization are usually sufficient at once to identify pyrite and distinguish it from other rock minerals. From pyrrhotite, $Fe_{11}S_{12}$, and chalcopyrite, $FeCuS_2$, other sulphides of iron which occasionally may be seen in rocks, the test of hardness discriminates it: chalcopyrite (3.5) can be readily scratched with the knife and gives reactions for copper; pyrrhotite has a bronze color, is also scratched by the knife, is magnetic, and gives little or no sulphur in the closed tube.

Occurrence. Pyrite is a mineral that has many different modes of origin and in consequence is found in all kinds of rocks as a scattered accessory component, usually in small distinct crystals, less commonly aggregated. The largest masses are found in ore deposits, chiefly formed in contact zones of igneous rocks through the action of mineralizing solutions. In igneous rocks it appears as a primary product of crystallization from the molten magma. In sedimentary rocks it is frequently found replacing fossils, and its occurrence must be due to reactions between the sulphur of albuminous materials of organic life and the iron in the rocks. It is common in coal seams.

Apatite

Apatite crystallizes in hexagonal prisms either rounded at the ends or capped by a six-sided pyramid. It is scratched by the knife, has a vitreous luster, and is white to green or brown in color. No good cleavage. Brittle. Transparent in small crystals to opaque in large. Very difficultly fusible. Dissolves in nitric acid, and ammonium molybdate solution added to a few drops of the nitric acid solution gives a bright yellow precipitate showing the presence of phosphorus. Composition $(CaF)Ca_4(PO_4)_3$; phosphate of calcium with fluorine; the fluorine is often replaced wholly or in part by chlorine. Apatite is found in large, sometimes huge, crystals in pegmatite dikes and in metamorphosed limestones in the crystalline schists; these may be said to be the chief megascopic modes of occurrence. In these, however, it cannot be said that its function as a rock-mineral is of any wide or general importance. In addition to this it occurs in minute microscopic crystals, which can seldom be detected with the eye or lens, in all kinds of igneous rocks and in many metamorphic ones. Microscopical study of the thin sections of such rocks has shown that in this form the mineral has a nearly universal distribution as a constant accessory component. Although the relative proportion of the mineral is small, rarely rising above two or three-tenths of one per cent of the rock, its presence is a matter of great importance, since by it the phosphorus, so necessary to vegetable and animal life (in bones, etc.), is furnished to the soil which is formed when the rocks decay and break down under the action of the various agents of weathering.

SEC. 2. *Hydrous Silicates*

The minerals of this group are of purely secondary origin; they are formed from previously existent ones by the agencies of weathering, water containing carbon dioxide or vegetable acids, and heated water or its vapors circulating in already solid, existent rocks. Thus the hydrous silicates do not play any important part in fresh, unchanged igneous rocks; only as these alter do they become of importance in them; their true home is in the metamorphic and sedimentary rocks, which at times are made up wholly of these minerals.

The important minerals to be considered in this section are *kaolin*, *chlorite*, *serpentine*, *talc*, and *zeolites*. Some micas would also naturally be considered here, and, among secondary minerals, limonite also, but, for reasons previously stated, these have been treated in the foregoing section.

Kaolin — Clay

Under the heading of clay are included certain hydrous silicates of aluminum having well-known physical properties by which they are distinguished. By far the most common and important of these is kaolin, which may be taken as a type of the group, and the only one which need be considered here in detail.

General Properties. Kaolin crystallizes in the monoclinic system, forming thin plates or scales, often with hexagonal outlines which are flexible and recall mica but are inelastic; these are generally so minute and so aggregated together that the crystal form is not a matter of importance in megascopic determination of the substance. Kaolin usually occurs in masses, either compact, friable, or mealy. The color is white, often tinted yellow, brown, or gray. Neither the hardness (2 to 2.5) nor the specific gravity (2.6) can be used for practical tests. On rubbing between the fingers kaolin has a smooth, unctuous, greasy feel, which helps to distinguish it from fine aggregates of some other minerals occurring in nature: thus its presence in soils can usually be told by rubbing out the fine, gritty particles of quartz, feldspar, etc., and observing whether there is a smooth, unctuous residue of clay.

It is infusible before the blowpipe, but if moistened with cobalt nitrate and ignited, turns blue, showing presence of aluminum. Heated in the closed glass tube, it yields water. It is insoluble in hydrochloric acid. In the phosphorus bead before the blowpipe, undissolved silica is left; this test helps to distinguish it from *bauxite*, a hydrated oxide of aluminum ($Al_2O(OH)_4$), which very much resembles it and sometimes occurs in considerable deposits. Bauxite dissolves in the phosphorus bead completely. The chemical composition of kaolin is $H_4Al_2Si_2O_9$, a combination of $Al_2O_3 . 2\,SiO_2 . 2\,H_2O$.

Occurrence. Kaolin is always a secondary mineral formed by the alteration or weathering of previously existent aluminous silicates, chiefly feldspar. The reaction by which it is formed from alkalic feldspar is one of the most important in nature, for by it soil is chiefly made and the alkali necessary for plant food liberated and converted into soluble form. It probably takes place somewhat as follows:

$$\begin{array}{lllllll}
\text{Orthoclase} & + \text{ Water} & + \text{ Carb. Diox.} & = \text{ Kaolin} & + \text{ Potas. Carb.} & + \text{ Quartz.} \\
2\,KAlSi_3O_8 & + 2\,H_2O & + \quad CO_2 & = H_4Al_2Si_2O_9 & + \quad K_2CO_3 & + 4\,SiO_2.
\end{array}$$

This process and reaction have already been described under feldspars. The feldspathoids also yield kaolin and the process could be expressed as follows:

$$\begin{array}{ccccccccc} \text{Nephelite} & + & \text{Water} & + & \text{Carb. Diox.} & = & \text{Kaolin} & + & \text{Sodium Carb.} \\ 2\,NaAlSiO_4 & + & 2\,H_2O & + & CO_2 & = & H_4Al_2Si_2O_9 & + & Na_2CO_3. \end{array}$$

They are more likely, however, first to change into muscovite or zeolites and these ultimately to clay.

From what has been said it is clear that feldspathic rocks furnish kaolin, and every stage of the change may be observed in nature, as described more completely in the chapter dealing with the origin of sedimentary rocks and soils. Thus kaolin occurs intimately mixed with the feldspar substance of such rocks as are undergoing this change; it is found occasionally in quite extensive deposits where such rocks have been completely altered in place, and the products of decay yet remain where they have been formed; and lastly it occurs in extensive beds in the sedimentary formations. Since the particles of kaolin are very minute, light, and flat they remain much longer in suspension than the other products of land waste, and thus in erosive and sedimentary processes there is a constant tendency to separate them from the other particles. We find beds of clay showing every degree of admixture with sand, etc., and passing into sandstones and other rocks, but not infrequently they are of a high degree of purity.

Chlorites

The chlorites are an ill-defined group of hydrous silicates so named on account of their green color (Greek χλωρός, green), which are always secondary and formed at the expense of previously existing silicate minerals which contain aluminum, iron, and magnesium. Outwardly they resemble the micas, but are unlike them in that their folia are soft and inelastic. They are hydrous silicates of aluminum with ferrous iron and magnesium. They have certain common properties by which they may generally be easily recognized as a group, but the identification of the different members is usually a difficult matter and for ordinary purposes of megascopic petrography of little importance. In the description which follows, then, it is these general group properties which are given, though these are based largely on the species clinochlore, which is perhaps the most common and best known of the group.

Form. The chlorites are really monoclinic in crystallization, but, as in the case of the micas, when crystal form can be observed they are generally in six-sided plates and tablets. More commonly they occur in irregular leaves and scales which are aggregated into fine granular or coarse leafy massive forms or arranged into fan-like or rosette-like groups. The scales are sometimes flat; often bent or curled.

General Properties. Chlorite, like mica, has a highly perfect cleavage in one direction parallel to the flat base of the plates. The cleavage leaves are flexible and tough but, unlike those of mica, they are inelastic. Luster of cleavage face rather pearly. Color green, variable, usually a rather dark green. Usually translucent. Hardness, 2 to 2.5 soft, just scratched by the finger nail. Specific gravity about 2.7. Streak pale green to white. The chemical composition of the chlorites is not definitely understood and seems to be complex: it may be illustrated by the formula assigned to clinochlore, $H_8(Mg,\ddot{F}e)_5Al_2Si_3O_{18}$, which may be written $4\ H_2O\ .\ 5\ (Mg,Fe)O\ .\ Al_2O_3\ .\ 3\ SiO_2$. Ferrous iron and magnesium are isomorphous. In kämmererite, a rare violet-red variety, part of the aluminum is replaced by trivalent chromium. Before the blowpipe chlorites are not fusible or very difficultly so; with the borax bead they react for iron. Heated in the closed glass tube, they yield water. They are insoluble or soluble with difficulty in hydrochloric acid but are decomposed in sulphuric acid. These reactions are those of the common kinds.

Occurrence. The chlorites are a widely spread group of minerals, and occur wherever previously existent rocks, containing silicates composed of aluminum, iron, and magnesium, such as dark micas, amphibole, pyroxene, and garnet, are being altered by geologic processes. To chlorite many igneous rocks owe their green color, the original ferromagnesian silicates having been broken down by decay and changed more or less completely into this substance. They tend to lose their original bright, clean appearance and hard, clear-cut fracture and become dull green and more or less soft and even earthy. This change can also be often observed in the case of single embedded crystals of the above-mentioned minerals, which become soft, dull green masses.

Chlorite is also of common occurrence in the schistose rocks; in chlorite schist it is the prominent component accompanied by other minerals; other schists often owe their green color to its presence, as in green slates for example. Thus in finely disseminated particles it is a common coloring matter.

Serpentine

General Properties. Serpentine is usually massive, sometimes finely granular; sometimes fibrous, the fibers fine, flexible, and easily separable, like those of amphibole asbestos. Massive varieties have a conchoidal or splintery fracture and a smooth, greasy feel. The color of massive varieties is green, bright yellowish green, olive green, to blackish green, or nearly black; the fibrous varieties are generally brownish, yellowish brown, pale brown, or nearly white. Luster of the massive varieties is greasy, wax-like, glimmering and usually feeble to dull; of fibrous varieties pearly to opalescent. Translucent to opaque. Hardness, 2.5 to 3.0; apparent greater hardness is caused by presence of remains of the original mineral or by infiltrated and deposited silica. Specific gravity somewhat variable, fibrous 2.2 to 2.4, massive 2.5 to 2.7. Composition, $H_4Mg_3Si_2O_9 = 2\ H_2O\ .\ 3\ MgO\ .\ 2\ SiO_2$. A small part of the MgO is usually replaced by ferrous oxide, FeO. Before the blowpipe, difficultly fusible, fine fibers fuse more readily. In the closed glass tube, serpentine yields water on ignition. The finely powdered or divided material decomposes in boiling hydrochloric acid with separation of silica but does not gelatinize. The solution may be tested for iron and magnesium. It is easily distinguished from epidote and other common green silicates which may resemble it, by its greasy feel and softness.

Occurrence. Serpentine is a secondary mineral resulting from the alteration of previously existing silicates rich in magnesium. Thus pyroxene, amphibole, and especially olivine may be altered to this substance. In the case of olivine the process can be illustrated by the following equation:

$$\begin{array}{ccccccccc} \text{Olivine} & + & \text{Water} & + & \text{Carb. Diox.} & = & \text{Serpentine} & + & \text{Magnesite} \\ 2\,Mg_2SiO_4 & + & 2\,H_2O & + & CO_2 & = & H_4Mg_3Si_2O_9 & + & MgCO_3 \end{array}$$

This would explain the frequent association of the mineral magnesite, $MgCO_3$, with serpentine; or if magnesite is not present, it may have been taken into solution by the carbonated water and removed.

A still simpler method of alteration to serpentine would be by the action of heated waters containing some soluble silica.

$$3\,Mg_2SiO_4 + 4\,H_2O + SiO_2 = 2\,H_4Mg_3Si_2O_9.$$

Therefore as a product of alteration of such minerals, especially by the action of heated waters, serpentine is a common and widely diffused mineral and is found both in igneous and metamorphic rocks. It may occur disseminated in small scattered masses in the rocks or form large independent bodies, as described further under the chapters dealing with the rocks. Besides the common massive form, many sub-varieties of serpentine are known; the most important of these is the finely fibrous one, the asbestos of commerce, which is known as *chrysotile.* It usually occurs in seams in the massive variety. Bright green massive material is known as precious serpentine and is cut for ornamental purposes.

Talc

General Properties. The exact crystal form of talc is doubtful, but this is not a matter of importance, since talc so rarely occurs in distinct crystals. It is usually seen in compact or strongly foliated masses, sometimes in scaly or platy aggregates which may be grouped into globular or rosette-like forms. Like mica, it has a perfect cleavage in one direction, but the laminæ though flexible are not elastic; it is sectile. It has a soft, greasy feel. The cleavage face has a mother-of-pearl luster. The color is white, often inclining to green; apple-green; sometimes gray to dark gray. Usually translucent. Hardness = 1 to 1.5, easily scratched with the finger nail. Specific gravity, 2.7 to 2.8. Streak, light, usually easily seen on dark cloth. Composition, $H_2Mg_3(SiO_3)_4$, acid metasilicate of magnesium. Before the blowpipe it whitens, exfoliates, and fuses with difficulty on the edges. Yields water in the closed glass tube only on intense ignition. Scarcely acted on by hydrochloric acid. It is easily recognized by the properties mentioned above. When in fine scales, however, it can not be distinguished from sericite except by chemical tests.

Occurrence. Talc is a secondary mineral produced by the action of circulating fluids on magnesium silicates, especially those free from aluminum, such as olivine, hypersthene, and some pyroxenes and amphiboles. The process could be illustrated by the following equation.

$$\begin{array}{lllllllll} \text{Enstatite} & + & \text{Water} & + & \text{Carb. Diox.} & = & \text{Talc} & + & \text{Magnesite} \\ 4\,MgSiO_3 & + & H_2O & + & CO_2 & = & H_2Mg_3(SiO_3)_4 & + & MgCO_3 \end{array}$$

Thus talc occurs at times in the igneous rocks as an alteration product of such silicates, especially in the peridotite and pyroxenite groups. The place, however, where it plays an important part is in the metamorphic rocks, where alone it may form independent masses, as in steatite or soapstone, or be an important component of several varieties of schistose rocks as in talcose schists.

Zeolites

The zeolites are a group of hydrous silicates, composed, like the feldspars, of aluminum with alkali and alkali-earth metals. They are indeed for the most part secondary minerals which have been formed at the expense of feldspars and feldspathoids by the action of heated circulating waters and steam, and are thus chiefly found in igneous and especially volcanic rocks. They do not form a group so closely related in crystallization and other properties as the feldspars, but still, in many ways, they have certain common properties by which they may be distinguished. These will first be described, and then, out of the many species, the individual characters of a few of the most important will be treated.

Group Properties. The zeolites are nearly always well crystallized, the crystals presenting the forms characteristic of the different species. They have a vitreous luster, are usually colorless or white, sometimes tinted yellow or red, like feldspar. They are usually of inferior hardness and can be scratched by the knife. Their specific gravity is low, 2.1 to 2.4. They fuse very readily before the blowpipe, most of them with intumescence (whence the name, *ζεῖν*, Greek, to boil), but some quietly, to white glasses or enamels. They dissolve in hydrochloric acid, sometimes gelatinizing and sometimes with separation of slimy silica. Some of the more common varieties are *analcite*, *natrolite*, *stilbite*, and *heulandite*.

Analcite. This zeolite crystallizes in isometric trapezohedrons like garnet, a property which easily enables one to recognize it. Generally colorless to white. Before the blowpipe first becomes opaque, then fuses quietly to a clear glass, coloring the flame yellow. Dissolves in hydrochloric acid with separation of silica but does not gelatinize. Its composition is $NaAl(SiO_3)_2 + H_2O$.

Natrolite. Crystallizes in orthorhombic prisms which are generally long, slender, and even needle-like and arranged in divergent bunches or compacted into fibrous, often radiating masses. Before the blowpipe fuses easily and quietly to a clear glass; fuses in a candle flame. Dissolves in acid with gelatinization. Composition, $Na_2Al(AlO)(SiO_3)_3 + 2\ H_2O$.

Stilbite. Crystallizes in complex monoclinic crystals, which are usually so compounded together that the aggregate has the form of a sheaf. There is a perfect cleavage in one direction and this appears on the side of the sheaf with pearly luster. Sometimes in divergent, sometimes in globular groups. White or red in color. Before the blowpipe swells, intumesces, and fuses to a white enamel. Dissolves in acid without gelatinization. Composition, $H_4(Ca,Na_2)Al_2(SiO_3)_6 + 4\ H_2O$.

Heulandite. Crystallizes in flattened monoclinic crystals which aggregate into compound individuals, the crystals being grown side by side with the flattened surfaces together. There is a perfect cleavage parallel to this flattened side, which has a pearly luster. The cleavage plates are often curved and have a lozenge-shaped outline. Blowpipe and chemical characters are like those of stilbite. Composition, $H_4CaAl_2(SiO_3)_6 + 3\ H_2O$.

Occurrence. As stated above, the zeolites are secondary minerals chiefly found in igneous rocks. They occur where the igneous rocks have been subjected to the action of circulating waters and steam which have attacked the feldspars and feldspathoids. Thus, for example, a mixture of albite and nephelite with water would yield analcite, as follows:

$$\begin{array}{ccccccc} \text{Albite} & + & \text{Nephelite} & + & \text{Water} & = & \text{Analcite} \\ NaAlSi_3O_8 & + & NaAlSiO_4 & + & 2\,H_2O & = & 2\,NaAl(SiO_3)_2 \,.\, H_2O \end{array}$$

Hence where feldspathic rocks have been somewhat altered they are very likely to contain zeolites in small amounts scattered through them; in some rare instances it has been found that a considerable part of the rock mass is composed of them, especially of analcite. Ordinarily the presence of these minerals is not to be detected megascopically, though it may be discovered by heating some of the powdered rock in a closed glass tube, whereupon the easy evolution of abundant water would indicate it.

Their especial home, from the megascopic point of view, is in the lavas, particularly basaltic ones. Here they are found coating and lining cavities and the sides of jointing planes, and composing the materials of the amygdules, as described under amygdaloidal structure and under basalt. They may be associated with crystals of quartz and of calcite in such occurrences, and, in addition to the common kinds mentioned above, many others may occur. The description of the less common kinds must be sought for in the larger manuals on minerals.

SEC. 3. *Carbonates*

The carbonates are salts of carbonic acid, H_2CO_3, and are secondary minerals, in that their metals have been derived from previously existent minerals acted upon by water and carbon dioxide, either from the supply already in the atmosphere or coming from interior sources deep within the Earth. The carbonates thus formed have either been deposited directly where we now find them, or, being soluble in water containing carbon dioxide, they have been carried in solution into lakes and into the sea and redeposited by the agencies of organic life in the form of chalk, limestone, etc. The shifting about of carbonates on the Earth's surface, owing to their solubility in water containing carbon dioxide, is a geologic process of great importance and gives rise to a variety of products which are described in their appropriate places as rock formations. Here they are treated simply as minerals and out of the considerable number of kinds only two are of such importance that they will be considered in detail — *calcite* and *dolomite.*

Calcite

Form. Calcite crystallizes in the rhombohedral system. The crystals are often very fine, perfect, and sometimes of very large size. It displays a great variety of crystal forms, many of them being often very complex. Some simple ones are shown in the annexed figures. Figure 51 is a simple flat rhombohedron, three faces above and three below. Figure 52 is the unit rhombohedron, so called because the faces are parallel to the cleavage. Figure 53 is a very acute rhombohedron. Figure 54 is a very short prism with six prism faces *m* and the flat rhombohedron *e* above and below; Figure 55 is similar but the prism faces *m* are elongated. Figure 56 is an acutely pointed form, the scalenohedron. All of these are common

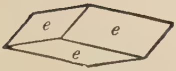

Fig. 51

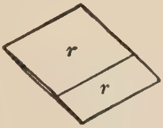

Fig. 52

Fig. 53

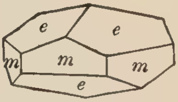

Fig. 54

crystal forms shown by calcite; they occur when it is found lining cavities in rocks, in druses, in amygdaloids, in geodes, and on the surfaces of joint planes and fissures and in caves; in short, in all those places where it could be deposited by infiltrating water containing it in solution. As a rock-making mineral it is massive; often crystalline-granular and coarse to fine in structure as in marble, or compact as in ordinary limestone, or loose and powdery in texture as in chalk. It is sometimes spongy in structure as in tufa, or rounded, stalactitic, mammillary, etc., as in cave deposits and in concretions, and not uncommonly fibrous.

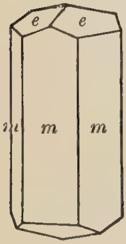

Fig. 55

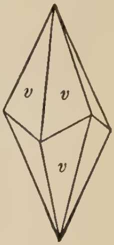

Fig. 56

Cleavage. Calcite has a very perfect rhombohedral cleavage, in three directions parallel to the faces *r* of the crystal shown in Fig. 52. While this is, of course, best produced in isolated crystals it can be well observed on the fractured surfaces of coarsely crystalline massive forms, as in many marbles and related rocks and in the massive calcite of veins. The angles of the face of the rhomb produced by cleavage are just about 78 and 102 degrees, as shown in Fig. 57, and small cleavage pieces can be readily tested by applying them to the edges of the figure on the paper.

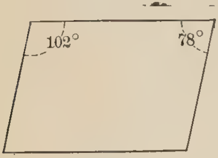

Fig. 57

General Properties. The hardness is 3; readily scratched or cut by the knife; chalky varieties are, of course, softer. The specific gravity is 2.71 if pure. Calcite is generally colorless or white but it frequently displays a great variety of exotic colors owing to the presence of impurities; thus it may be reddish or yellowish from iron oxides, gray to black from organic matter, or green, purple, blue, etc., from other substances. Streak, white to gray. The luster of the crystallized calcite is vitreous; of massive forms glimmering to dull. In the same way it varies from transparent to translucent to opaque.

Chemical composition, $CaCO_3$; or $CaO \,.\, CO_2$. $CaO = 56$ per cent, $CO_2 = 44$ per cent; total = 100.

Before the blowpipe it is infusible, colors the flame reddish yellow, and after ignition if placed on moistened yellow turmeric paper colors it brown. Fragments effervesce freely in *cold* (difference from dolomite) very dilute acids.

Occurrence. Calcite is one of the most common and widely diffused of all minerals. It occurs in the igneous rocks as the result of alteration of the calcium-bearing silicates by waters containing carbon dioxide in solution, other substances being formed as by-products at the same time. Thus, for example,

$$\begin{array}{ccccccccccc} \text{Pyroxene} & + & \text{Water} & + & \text{Carb. Diox.} & = & \text{Calcite} & + & \text{Serpentine} & + & \text{Quartz} \\ 3\,CaMg(SiO_3)_2 & + & 2\,H_2O & + & 3\,CO_2 & = & 3\,CaCO_3 & + & H_4Mg_3Si_2O_9 & + & 4\,SiO_2 \end{array}$$

The calcite thus formed may remain for a time in the rock but eventually, as the latter breaks down into soil, it is to a greater or lesser extent removed in solution and carried away. The mineral has also been found to occur very commonly in minute cavities in unaltered igneous rocks, especially intrusive ones, and its origin is probably due to infiltration and deposition of the material from neighboring rock masses. In these cases just mentioned, the mineral is ordinarily not observable megascopically, but its presence is easily ascertained by immersing a fragment of the rock in cold dilute acid and seeing if it effervesces and gives off carbonic acid gas. Calcite also occurs in amygdaloidal cavities in lavas, especially in basalts, and often in good crystals.

In the sedimentary and metamorphic rocks calcite plays a much more important part. It is very commonly found distributed through them in fine particles or acting as a cement to the other mineral granules. From this rôle, if we examine a whole series of these rocks, we find it increasing more and more in abundance and importance as a constituent, until finally there are enormous, widely extended rock masses, such as the chalks, limestones, and marbles, composed practically and in some instances wholly of this substance. Such rocks are described in their appropriate places in this work; it is sufficient here to mention that in the sedimentary rocks calcite plays an important part in chalk, limestone, calcareous marls, calcareous sandstones, etc.; in chemical deposits in calcareous tufas, sinters, stalagmitic deposits, veins, etc., and in the metamorphic rocks in marbles and in rocks that are mixtures of calcite and various silicates.

Determination. Calcite, when sufficiently coarsely crystallized, is easily recognized by its inferior hardness and rhombohedral cleavage. This determination is confirmed chemically by its ready solubility in cold dilute acids with effervescence of CO_2 gas and if necessary by a test for the presence of calcium. For the distinction from dolomite, reference should be made to the description of that mineral.

Dolomite

Form. Dolomite crystallizes in the rhombohedral system and, like calcite, it is found in simple rhombohedral crystals the faces of which are parallel to the cleavage; Fig. 52 of calcite. Unlike that mineral, it rarely occurs in complicated crystals, and the simple rhombohedron, in which it is generally seen when showing outward crystal form, usually has its faces curved as represented in Fig. 58 instead of flat. Moreover, the curved crystals are likely to be compound, made up of a number of sub-individuals. This is the way it occurs when lining druses and cavities, but as a rock-making mineral it is nearly always massive, often crystalline-granular and coarse to fine in texture as in some marbles. It is also often compact-massive as in some limestones; more rarely columnar or fibrous.

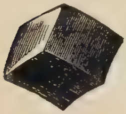

Fig. 58

Cleavage. The cleavage, like that of calcite, is perfect in three directions parallel to the faces of the simple rhombohedron. The angles of the cleavage rhombs differ only a degree or so (74 and 106 degrees, nearly) from those of calcite and therefore by form alone they cannot be distinguished from calcite by the eye.

General Properties. The natural color is white, and while this is often seen the mineral is very likely to be tinted some exotic color by other substances; thus it may be reddish, brown, greenish, gray, or even black. Luster vitreous, sometimes pearly to dull or glimmering in compact varieties. Translucent to opaque. The hardness is 3.5 to 4.0, harder than calcite but easily scratched with a knife. Specific gravity, 2.8 to 2.9. Chemical composition, $CaMg(CO_3)_2$; CaO 30.4, MgO 21.7, CO_2 47.9; sum = 100. Before the blowpipe infusible, but placed on moist turmeric paper after ignition colors it brown. If unpowdered does not dissolve or is very little acted upon in cold dilute acid, but on boiling effervesces and goes into solution (difference from calcite). The solution may be tested for calcium and magnesium as directed in the chapter on mineral tests.

Occurrence. Dolomite occurs as a scattered accessory component of certain crystalline schists and in beds of gypsum, etc., but its chief importance as a rock-making mineral lies in the fact that alone it forms immense extended beds both in the sedimentary series and in the metamorphic rocks. It thus exactly parallels calcite, and in limestones and in marbles we have every degree of transition between these two substances, — marbles composed of calcite alone, others with increasing amounts of dolomite until pure dolomite marble is reached. This is more fully described under the carbonate rocks.

Determination. The rhombohedral cleavage and inferior hardness separate dolomite, like calcite, from other common rock minerals. The frequent curved surfaces help to distinguish it from calcite but the test with hot and cold acid mentioned above, together with the finding of magnesium in the solution, is the only safe way.

Siderite, Magnesite, and Breunerite. As an appendix to the description of calcite and dolomite, these carbonates, which are sometimes of local importance, may be mentioned. Siderite or spathic iron ore is

$FeCO_3$, ferrous carbonate, while magnesite is magnesium carbonate, $MgCO_3$, and breunerite is an isomorphous mixture of the two, $(Mg,Fe)CO_3$. In crystallization, cleavage, hardness, etc., they closely resemble the other carbonates described. Siderite is usually light to dark brown in color; magnesite white; breunerite brownish. Siderite chiefly occurs more or less massive and impure in certain sedimentary deposits, as the so-called "clay iron stone" and is a valuable ore of iron. Magnesite occurs chiefly in certain metamorphic rocks and is often associated with serpentine, talc, etc. It may be accompanied or replaced by breunerite.

SEC. 4. *Sulphates*

The sulphates, like the carbonates, are in general minerals of a secondary nature; the metals they contain have been taken from previously existent minerals, the sulphuric acid has been furnished for the most part by the oxidation of metallic sulphides or by exhalations in regions of igneous activity. With a few exceptions they are readily soluble, and the great bulk of them that has been formed during geologic time has therefore been transferred to the sea, which, with the salt lakes in the interior of continents, is now the great reservoir of these substances as well as of many other soluble salts such as the chlorides. As rock-making minerals, only two of the large number of sulphates known are of importance, *gypsum* and *anhydrite*. Barite, $BaSO_4$, which is one of the few insoluble sulphates, is a very common material in veins and is also found in concretions, but it does not form independent rock masses or play any rôle as a rock-component as the two first mentioned do.

Gypsum — Selenite

Form. Gypsum crystallizes in the monoclinic system, and the common form of the crystals is shown in Fig. 59. The same crystal is shown in Fig. 60 revolved so that the side face *b* is parallel with the plane of the paper; such crystals may be roughly tested by placing them on the diagram and seeing if the angles coincide. Twin crystals are common and they tend to assume arrow-head forms as shown in Fig. 61. More commonly, as a rock constituent, gypsum is massive, foliated, often with curved surfaces, or granular to compact and sometimes fibrous.

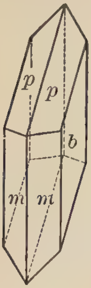

Fig. 59

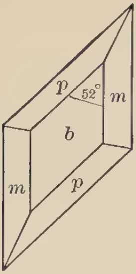

Fig. 60

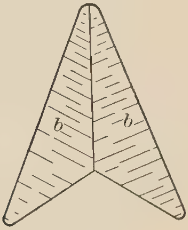

Fig. 61

Cleavage. Gypsum has a perfect cleavage parallel to the side face *b*; by means of it on good material very thin sheets with perfect luster may be split off, almost as in mica. Such sheets will be found to break in one direction in straight lines with a conchoidal fracture; this is due to another cleavage parallel to the vertical edge between *mm*. If such sheets be bent, cracks will appear in them, making angles of 66 and 114 degrees with the straight fracture edge mentioned above; if the bending parallel to this direction is continued the plate will break with a fibrous fracture, and a cleavage rhomb like that shown in Fig. 62 may be obtained. In massive coarsely crystalline gypsum, these cleavages can usually be readily obtained and furnish one means of helping to identify it; in fibrous material it simply cleaves parallel to the fibers; in the compact massive forms it may happen that no cleavage is seen.

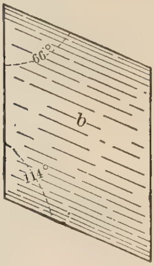

Fig. 62

General Properties. Gypsum is naturally colorless or white, and the crystals are transparent to translucent, but it is frequently tinted reddish or yellowish or in massive varieties may be even red, brown, or black through impurities, and translucent to opaque. The luster of the cleavage face *b* is glassy to pearly, of fibrous varieties satiny, while massive forms are glistening, glimmering to dull. Streak, white. Hardness, 1.5 to 2.0, easily scratched by the finger nail. Specific gravity of pure crystals, 2.32. Chemical composition, hydrous sulphate of calcium, $CaSO_4 + 2\,H_2O$. CaO 32.5, SO_3 46.6, H_2O 20.9; sum = 100. Before the blowpipe fuses easily and after ignition colors moistened turmeric paper brown. Fused with carbonate of soda and charcoal dust on charcoal and transferred to a moistened surface of silver, stains it dark. Finely powdered mineral is readily soluble in boiling dilute hydrochloric acid. Heated intensely in a closed glass tube, it gives off water and becomes opaque. Heated moderately (not above 200 degrees) it loses some water and becomes plaster of Paris and the powder, if moistened, again takes up water and sets or becomes solid, turning back into gypsum. If heated too highly it loses all its water, becomes anhydrite, $CaSO_4$, and is then called dead-burnt plaster and does not set as described above.

The occurrence of gypsum is mentioned later in its description as a stratified rock.

Anhydrite

General Properties. Anhydrite crystallizes in the orthorhombic system. In the rocks in which it occurs it is seen in granular to compact masses, less commonly in fibrous or foliated forms. It has a cleavage in three directions at right angles, and if coarsely crystalline this may be observed to produce cube-like forms. Usually white but sometimes tinted as in gypsum; luster of cleavage faces pearly to glassy; in massive varieties varies to dull. Harder than gypsum = 3 to 3.5 but easily cut by knife. Specific gravity, 2.95. Chemical composition, $CaSO_4$; CaO 41.2, SO_3 58.8 = 100. Blowpipe and other reactions as with gypsum, but it does not yield water in the closed glass tube on heating, which is the best distinction from gypsum; the difference in cleavage also aids in the discrimination.

Occurrence. Like gypsum, anhydrite forms interstratified beds in sedimentary formations, especially in limestones and shales. It is also found in masses and in geodes in such rocks and is a common associate of rock salt and gypsum.

Rock Salt — Halite

Rock salt, sodium chloride, NaCl, is the only chloride that occurs as a rock-forming constituent in such amounts as to be of importance. It is easily recognized by its cubic crystals, perfect cubic cleavage, solubility, and saline taste. Colorless and transparent to white, translucent; frequently tinted various colors by impurities. Hardness = 2.5. Occurs in beds, sometimes of enormous thickness, in the sedimentary formations, usually clays or shales, and is frequently accompanied by gypsum and anhydrite.

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CHAPTER V

THE DETERMINATION OF ROCK MINERALS

The more important of the physical properties of the rock minerals have been described in the previous chapter, and the methods by which most of these are to be determined have been stated. In the present chapter it is proposed to present a number of qualitative chemical tests, which can generally be made with a few reagents and simple apparatus, and which are of great service in mineral determination and in thus aiding to classify rocks. These are followed by two tables: one for rough approximations in the field, the other for more complete identifications in the laboratory by means of the properties and methods described.

Chemical Tests

These consist mainly in observing the effect of acids upon the mineral, whether it is dissolved or only partly attacked or is wholly insoluble; if soluble, or partly so, the solution is treated with certain reagents in order to ascertain what substances have gone into solution. These reagents serve to detect the acid radicals and the metals that compose the rock minerals. A few useful additional tests are given.

A. **Powdering the Sample.** The first thing to do in testing the solubility of minerals is to prepare a finely powdered sample. Small chips, grains, or splinters of the substance, about the size of wheat grains and as pure as possible, are successively crushed and ground to a fine powder, like flour, in a diamond, steel, or agate mortar, until a sufficient amount has been prepared. It is usually best to crush the fragments in the steel mortar, and unless a test for iron is to be applied they may be ground in this as well. The finer the powder is ground the more readily it will go into solution; it is therefore generally best to grind it until it no longer feels gritty when a small pinch is rubbed between the fingers.

B. **Treatment with Acid.** A small bulk of the powder prepared as above, about equal to a pea in volume, is put in a test tube, covered with about an inch of distilled water and a few drops of nitric or hydrochloric acid added. Either may be used, but if it is desired to test the solution subsequently for phosphorus or chlorine the nitric acid should be employed. If the cold acid has no apparent effect upon the substance, the test tube may then be gently heated over the flame of a Bunsen burner or lamp of a suitable kind until the liquid is brought to boiling. If the effect is slight or apparently none has been produced, more acid is added and the boiling repeated until the substance is brought into solution or it is apparent that it cannot be dissolved.

C. **Carbonic Acid — Carbonates.** If the mineral effervesces freely in cold dilute acid this indicates that it is a carbonate and that CO_2 gas is being given off. It is probably calcite or dolomite. The common rock-making carbonates are calcite (carbonate of calcium) and dolomite (carbonate of calcium and magnesium). Calcite will effervesce freely with cold acid either in an uncrushed fragment or in a powder. Dolomite, on the other hand, will not effervesce freely with cold acid unless it is reduced to a powder. Upon treatment of a fragment with hot acid, dolomite will effervesce readily and this action will, of course, be greatly accelerated if the mineral is reduced to a powder. This difference of behavior serves as a convenient means of distinction between calcite and dolomite, which may be confirmed by tests for calcium and magnesium as given below. The rare rock mineral cancrinite, a silicate containing CO_2, also effervesces very slowly in hot dilute acid; the heated solution should be examined in a good light with a lens, when a slow persistent evolution of minute bubbles will be seen. In observing the heated solution care must be taken not to confuse the ebullition of steam bubbles with the effervescence of CO_2

gas; a moment's pause should be given to allow the former to cease.

D. **Soluble Silicates. Gelatinization.** If the substance treated according to A wholly or partly dissolves without effervescence it should be tested for soluble silica. If it is only partly attacked the insoluble portion should be filtered off and the filtrate used. This is boiled down in the test tube, which is continuously and gently shaken to prevent cracking, until the solution is greatly concentrated, if necessary to a few drops. It is then allowed to cool and stand, and if it becomes a jelly the presence of soluble silica is indicated. If the amount of silicate that has gone into solution is relatively large, a jelly will probably form while the solution is being boiled down and is still hot, otherwise the solution must be concentrated and allowed to stand, as just stated; care must be taken not to confuse the true jelly of soluble silica with a thickening of the cooled solution owing to concentration in it of the salts, especially basic salts of iron. If the solution is carefully carried to dryness and the residue heated for a few moments, the salts, on being moistened with strong hydrochloric acid and then warmed, will go into solution in water, while the silica is left as an insoluble residue and may be filtered off. The filtrate can be tested for the various metallic bases, aluminum, iron, calcium, etc., which may be in solution, by the methods described below.

The rock-making silicates that will go into solution on boiling with nitric or hydrochloric acid are nephelite, sodalite, analcite, olivine, chondrodite, serpentine, anorthite, leucite, noselite, stilbite, heulandite, and cancrinite. All except serpentine, leucite, analcite, stilbite, and heulandite yield gelatinous silica; with these when the liquid is boiled it turns from the milkiness caused by the suspended material to a translucent appearance with slimy silica suspended in it. The bases, however, have gone into solution.

E. **Insoluble Silicates. Fusion.** Most rock-making silicates are insoluble in acids or only partially soluble. To get them into solution so that one may test for the bases as described in the following sections, a preliminary process of fusion with sodium carbonate, Na_2CO_3, must be undertaken. For this purpose some of the powder obtained in A is mixed with about 4 to 5 times its weight of dry anhydrous sodium carbonate, placed in a platinum crucible or spoon, and gently heated to redness over a Bunsen lamp flame. If no crucible is at hand a coil of platinum wire can be used instead; the mixed powder is made into a thick paste with a little water, and a quantity taken on the coil and carefully fused before the blowpipe. A fused bead or mass the size of a large pea may be obtained in this way. The fusion must be conducted until bubbling has ceased.

In this fusion the silicates are decomposed, and silica is liberated from them and takes the place of the carbonic acid in the sodium carbonate, which is thus converted into sodium silicate. The liberated CO_2 gas is given off with bubbling and frothing of the fusion and this effect is in itself indicative of the presence of silica in the original substance, provided it is known by previous trial not to come from combined water. The reaction might be illustrated in the case of pyroxene as follows:

$$CaMgSi_2O_6 + 2\ Na_2CO_3 = 2\ Na_2SiO_3 + MgO + CaO + 2\ CO_2.$$

The fused mass obtained is broken up in a diamond mortar, placed in a test tube, and then treated with acid until dissolved, evaporated and the silica separated and the metallic bases brought into solution just as directed for soluble silicates in D.

If the fusion has been made in a platinum crucible the cake can generally be loosened and removed by boiling with a little water; if not, it is dissolved with water and acid in the crucible, the latter being set in a beaker or dish.

F. **Aluminum.** The filtrate from the silica obtained in D or ED combined may be tested for aluminum. It is heated to boiling after addition of a few drops of nitric acid, and ammonia is added in slight excess. If a white or light-colored, flocculent, gelatinous precipitate forms, this is aluminum hydroxide. If it is reddish brown, then it is wholly or in part ferric hydroxide, indicating the presence of iron, which is very likely to be present in silicates, especially colored ones, and the aluminum may be masked.

If much magnesium is present in the mineral its hydroxide may also be precipitated at this point by the ammonia, unless the solutions are rather diluted and a considerable quantity of ammonium chloride or nitrate has been formed by the neutralization of the acid by the ammonia.

Scrape some of the precipitate from the filter paper, transfer it to a clean test tube, or if it is small in amount transfer it paper and all, and cover with about 5 cubic centimeters of water; drop in a piece of pure caustic potash, KOH, about the size of a pea, and boil. The aluminum, if present, will go into solution leaving the iron hydroxide undissolved; the latter may now be filtered off. Make the filtrate slightly acid with hydrochloric acid, boil and then add ammonia in slight excess; aluminum, if present, will be precipitated as the white flocculent hydroxide.

Aluminum can also be detected before the blowpipe by intensely heating the powdered mineral, moistened with cobalt nitrate, on charcoal. The presence of aluminum is indicated by the mass turning blue, as mentioned under topaz, cyanite, etc., in the following tables.

G. **Iron.** The detection of this metal has been mentioned above in F. A more delicate method is to add a few drops of potassium ferrocyanide solution to a few drops in water of the final filtrate obtained in D or ED combined, after boiling with a few drops of nitric acid in case hydrochloric was originally used. The formation of a deep Prussian blue precipitate or coloration, if the solutions are very dilute, indicates the presence of iron. The nitric acid converts the ferrous salt in the solution into a ferric one. Potassium *ferro*cyanide produces a Prussian blue with *ferric* salts, not with ferrous, while conversely potassium *ferri*cyanide produces the same effect with *ferrous* salts. Thus by testing portions of the original solution of the mineral in hydrochloric acid with these two reagents, the state or states of oxidation of the iron in the original mineral can be ascertained.

Iron is also shown when minerals become magnetic after being heated in the reducing flame of the blowpipe.

H. **Calcium.** The ammoniacal filtrate from the hydroxides of aluminum and iron obtained in F, or the clear liquid in case ammonia failed to precipitate, may contain calcium salts in solution. To prove the presence of calcium the liquid should be heated to boiling and some ammonium oxalate added, whereupon the formation of a precipitate of calcium oxalate proves the presence of this element. If it should be desired to test the solution further for magnesium, the calcium oxalate must be removed by filtration; it is allowed to stand for some time and then filtered; if the filtrate runs through turbid it should be again passed through the paper until the liquid is clear. To this a little more ammonium oxalate is added to prove the complete precipitation of the calcium.

I. **Magnesium.** Ordinarily the test for this element should not be applied until the aluminum, iron, and calcium have been removed, as directed in F and H, or their absence ascertained. To the solution thus obtained some sodium phosphate and a considerable quantity of strong ammonia are added. The formation of a precipitate, ammonium magnesium phosphate, proves the presence of this element. If a precipitate does not form at once it is not, however, safe to consider magnesium absent, for if the amount is small and the solution warm it may not appear until the liquid has become cold and has stood for some time. It is then likely to appear as a crystalline precipitate attached to the walls of the vessel.

J. **Sodium.** A mineral containing sodium, when heated before the blowpipe, colors the flame bright yellow. The best effect is obtained with silicates when the powdered mineral is previously mixed with an equal volume of powdered gypsum and a little of this taken upon a clean moistened platinum wire which has been previously tested. The reaction is, however, so delicate and produced so strongly by minute quantities of the element or accidental traces that great judgment must be used in employing it. It is only when the coloration is very intense and prolonged that the presence of sodium as an essential constituent should be inferred.

K. **Potassium.** This element may be detected by the violet color it communicates to the Bunsen or blowpipe flame. In silicates it is best obtained by powdering the mineral and mixing it with gypsum, as mentioned under sodium in J. The flame color is delicate and entirely obscured by any sodium present; it can however be seen by viewing it through a piece of thick, dark blue glass which cuts off all but the potassium flame. Through this it will appear of a violet or reddish purple.

Another test is to take a small portion of the final filtrate obtained in D or ED combined, evaporate it to a very small volume, add an equal volume of alcohol and, if it is turbid, filter it. Then add a few drops of hydrochlor-platinic acid, H_2PtCl_6, and if a heavy yellow or orange colored crystalline precipitate, potassium platinic chloride, K_2PtCl_6, forms it shows the presence of this element. No ammonium salt must be present or it will yield a similar precipitate.

L. **Hydrogen — Water.** If a little of the powdered mineral be placed in a glass tube, one end of which has been closed by fusion and drawing off, and gently heated below redness, the evolution of water, which collects on the upper walls of the tube, shows that it contains loosely attached *water of crystallization.* This occurs with zeolites, such as analcite, $NaAlSi_2O_6 + H_2O$, and with gypsum, $CaSO_4 + 2\,H_2O$. On the other hand, some minerals, including many silicates, contain hydrogen and oxygen firmly attached in the form of *hydroxyl* $-OH$, and this is only given off as water at a very high heat. Indeed with some, as for instance staurolite and talc, $Mg_3Si_4O_{10}(OH)_2$, it is necessary to subject the assay to intense ignition by heating it white hot before the blowpipe before the water is given off. This difference in behavior will often serve as a useful test in determining minerals. Many minerals that contain hydroxyl also contain fluorine and here it will often be found that the water evolved in the tube gives an acid reaction to test paper and the glass may be etched. Unless the latter occurs the test is not, however, decisive evidence of the absence or presence of fluorine.

M. **Fluorine.** This is best tested for as described under topaz, on page 78, in a bulb tube with sodium metaphosphate.

N. **Chlorine.** This occurs in rock salt, apatite, and sodalite. The test is the precipitation of chlorine as silver chloride, AgCl, in the solution by addition of a few drops of silver nitrate. The white precipitate turns bluish gray on exposure to light. The test for chlorine is very delicate and slight impurities may cause a faint opalescence in the liquid on addition of the silver salt. Rock salt is easily told by its solubility in water, taste, and associations. Apatite usually contains only a very little chlorine, yielding a faint test, or chlorine may be wanting in it. Sodalite dissolves in dilute nitric acid and silver nitrate produces in this a considerable precipitate of the chloride; the nitric acid solution also yields gelatinous silica as in D; these tests suffice to identify the mineral.

O. **Sulphuric Acid.** Barium chloride produces in the solution containing a sulphate a heavy white precipitate of barium sulphate, $BaSO_4$, insoluble in hydrochloric or nitric acid. Gypsum, anhydrite, and noselite contain sulphuric acid; they dissolve in hydrochloric acid and it may be tested for as above. Noselite also yields gelatinous silica, as in D, and the two reactions serve to identify it.

P. **Phosphoric Acid.** Dissolve the powdered mineral (see A) in nitric acid and add some solution of ammonium molybdate, whereupon a yellow precipitate of ammonium phosphomolybdate shows the presence of phosphorus. This test is very delicate. It should be conducted with cold or nearly cold solutions. The precipitate is soluble in excess of ammonia. If it is desired to make this test in a mixture of minerals, as in a fine-grained rock for instance, and silica may be in the solution, it is best to evaporate the latter and get rid of the silica as directed in D. The test for phosphoric acid can then be applied to the filtrate acidified with nitric acid. Apatite is the only common rock-making mineral containing phosphoric acid, and its presence in rocks and soils can usually be shown by this test when it cannot be detected megascopically.

Tables for the Megascopic Determination of Rock Minerals

The two tables that follow will be found useful in helping to identify the commoner rock-making minerals. Besides those given in the tables there are many less common minerals which enter into the composition of rocks and which may at times become of local importance. This is especially true in metamorphic limestones and schists. Some of the more important minerals have been described in the preceding chapter on the characters of minerals, but only about fifty minerals or mineral groups constituting the kinds that are ordinarily met with in megascopic rock study are here included. The tables can only be used to distinguish from one another the minerals that are named in them; they cannot in general be used to distinguish them from all other minerals. If doubt arises and a mineral seems to be other than any of those described here, the larger manuals of descriptive and determinative mineralogy must be consulted for its identification.

Table 1. This is based solely on the most obvious and easily determinable physical properties and includes about thirty common minerals or mineral groups. It may often be used to advantage in the field. The only apparatus required in its use is a lens, a pocket knife, and fragments of quartz and feldspar, in addition to the hammers usually carried. It will be of advantage to have one blade of the knife magnetized. The streak or color of the powdered mineral can be tested by grinding a small piece to powder between two hammer faces, pouring it on a piece of white paper, and rubbing the dust with the finger to observe the color produced. A piece may be cracked into smaller grains and these examined with the lens to observe the cleavage if it is not well shown by the mineral on the fractured rock surface. The transparency or translucency, if not obvious in the mineral in the rock, may be tested by holding a fragment or sliver against the light and observing whether

light is transmitted through its thinnest edges. The hardness is best tested on a smooth, lustrous cleavage face with the knife point or a sharp-pointed fragment of quartz or feldspar, substances which are usually readily obtainable.

Table 2. This includes about fifty of the prominent rock minerals or mineral groups the characters of which are treated in the foregoing descriptive portion. It requires for its use some of the simpler apparatus and reagents found in every chemical and mineralogical laboratory, and the knowledge that enables one to use them. They have been already mentioned on page 12.

The table is based upon those of the Brush-Penfield Determinative Mineralogy which have been modified to meet the demands of this particular place, and if further information is desired that manual may be consulted to advantage.

This table is much more complete and certain in its identification than Table 1 and should always be used in preference to it when possible. Table 1 is to be considered a more or less rough method of approximation to be used in the field or when no apparatus or reagents are at hand.

It should be repeated that the table cannot be used for the identification of all minerals that occur in rocks but only to distinguish the commoner ones, mentioned in it, from one another. The identification of the mineral is generally complete, but instances may occur where some comparatively rare one will give similar reactions. Thus the rare mineral aragonite would lead to the same place as calcite, but reference to the description of the latter would show at once that it differs markedly in other properties, such as cleavage and crystallization. This will usually be found to be the case, and if further information is desired it must be sought elsewhere. But within the limits imposed the table should serve a useful purpose to the student of rocks.

TABLE 1

The mineral has a fine cleavage in one direction; is sometimes micaceous and may be split into thin leaves by the use of the knife point. Sec. 1 below.

Has a good cleavage in two directions. Sec. 2.

Has a good cleavage in three directions, forming cubes or rhombs. Sec. 3.

Has a fine fibrous structure and cleavage. Sec. 4.

No apparent good cleavage. Sec. 5.

Sec. 1. *Cleavage in one direction*

A. Micaceous. Cleavage leaves tough, flexible, *elastic.* Occurs in crystals, shreds, flakes. Black, brown, gray or white. Transparent-translucent. *Mica,* p. 48.

B. Micaceous. Cleavage leaves tough, flexible, *non-elastic.* In crystals, shreds, masses. Usually green to dark green. *Chlorite,* p. 94.

C. Often micaceous. Leaves flexible but *non-elastic.* Greasy feel, very soft, marks cloth. White, greenish, gray. Usually in foliated masses. Translucent. *Talc,* p. 97.

D. Leaves somewhat flexible but showing cross cleavage cracks when bent, in one direction fibrous, in the other brittle forming rhombs. Soft; scratched by finger nail, but not greasy in feel. Usually colorless, white or reddish; transparent to translucent. In crystals, masses, seams. *Gypsum,* p. 106.

E. Leaves have a brilliant metallic luster, like polished steel. *Hematite* (micaceous variety), p. 87.

F. Leaves brittle; lozenge-shaped outline. Usually white, translucent. Scratched by the knife. Crystals in cavities. *Heulandite,* p. 99.

G. Not micaceous, massive, brittle. Very hard, not scratched by knife or feldspar. Yellowish green to dark green, translucent. In crystals or masses. *Epidote,* p. 70.

Sec. 2. *Cleavage in two directions*

A. Two cleavages at or very nearly at 90 degrees. Brittle, hard, not scratched by knife but by quartz. Usually of a light color, white, pink to red or gray, translucent. In crystals, grains, masses. *Feldspar,* p. 33.

B. Usually of a dark color, greenish to black; in grains or short prisms; sometimes light-colored in metamorphic rocks and then often elongated columnar in cleavage direction. Cleavage good but not eminent; prismatic. Cleavage angles 87 and 93 degrees. Usually scratched by feldspar. *Pyroxene,* p. 53.

C. Usually of a dark color, greenish to black. Generally in crystals elongated or bladed in cleavage direction. Sometimes light colored in metamorphic rocks. Cleavage very good with shining surface. Cleavage angles 55 and 125 degrees. Usually scratched by feldspar. *Amphibole*, p. 58.

Sec. 3. *Cleavage in three directions*

A. Cleavages not at right angles, forming rhombs. Easily scratched by knife. Usually white, sometimes tinted various shades to black; transparent to translucent. In crystals, masses, veins, etc. *Calcite*, p. 105, or *Dolomite*, p. 104. (If rhombic surfaces of crystals are curved, probably dolomite.)

B. Cleavages at right angles forming cubes, soluble, strong saline taste. Transparent colorless or white, rarely tinted. In crystalline masses. *Halite*, rock salt, p. 109.

C. Cleavage apparently as above. No perceptible taste. Easily scratched by the knife. White, bluish. In crystalline masses. *Anhydrite*, p. 108.

D. Apparent cleavages sometimes forming rhombs, sometimes apparently cubic. Very hard, scratches quartz easily. In hexagonal crystals, grains or lumps of a dark, smoky, or bluish gray; more or less translucent. *Corundum*, p. 83.

Sec. 4. *Has a fine fibrous or columnar structure*

A. In opaque brown to black masses. Streak yellow-brown. *Limonite*, p. 89.

B. In opaque red-brown to black masses. Streak brownish red. *Hematite*, p. 87.

C. White or reddish; translucent. Brittle. Often radially fibrous. Sometimes showing slender prismatic crystals. Difficultly scratched by the knife. Occurs in cavities, veins, or seams. *Natrolite*, p. 99.

D. White or reddish; translucent or transparent. Brittle. Often radially fibrous. Compound crystals often sheaf-shaped. Scratched by knife. In cavities, veins, or seams. *Stilbite*, p. 99.

E. Shreds easily into fine, flexible fibers like cotton or silk. White or light gray. *a. Hornblende asbestos*, p. 63. *b.* White to yellowish brown; silky; generally in veins in or associated with serpentine. *Chrysotile* (serpentine) *asbestos*, p. 97.

F. White or pale colors. Translucent. Brittle. Easily scratched by knife but not by finger nail. In masses. *Calcite*, p. 101.

G. White to pale red. Silky luster, translucent. Brittle, soft, scratched by finger nail. In masses and seams. *Gypsum*, p. 106.

SEC. 5. *Without good or apparent cleavage*

A. Opaque, brass-yellow crystals with metallic luster. Not scratched by the knife. *Pyrite,* p. 90.

B. Opaque, earthy, brown to brown-black masses. Streak yellow-brown. Scratched by the knife. *Limonite,* p. 89.

C. Opaque, reddish brown to black masses, or crystals and grains, iron black with metallic luster. Streak brownish red. Scratched by the knife. *Hematite,* p. 87.

D. Opaque, iron black masses, grains, or octahedrons with metallic luster. Streak black. Magnetic. Not scratched by the knife. *Magnetite,* p. 85.

E. Opaque, black grains or masses often with reddish tone. Luster metallic to submetallic. Streak black to reddish black. Not noticeably magnetic. Scarcely or not scratched by the knife. *Ilmenite,* p. 86.

F. In garnet-shaped crystals or spherical. Usually dark red to black and translucent. Brittle. Not scratched by feldspar. *Garnet,* p. 67.

G. In garnet-shaped crystals. Colorless or white to gray-white, translucent. Not scratched by knife but by feldspar. *Leucite,* p. 47, or *Analcite,* p. 99.

H. In transparent to translucent crystals or grains of a light yellowish- or bottle-green color. Not scratched by feldspar. *Olivine,* p. 64.

I. In prismatic crystals, generally slender, shiny, and black with triangular cross section. Not scratched by quartz. *Tourmaline,* p. 75.

J. In grains, masses, or hexagonal, pyramidal crystals. Conchoidal fracture. Greasy to glassy luster. Colorless, white, smoky, dark; transparent to translucent. Not scratched by feldspar. *Quartz,* p. 80.

K. In grains or masses, rarely in crystals with rectangular or hexagonal sections. Conchoidal fracture. Greasy, oily luster. White, gray, or reddish; translucent. Scratched by feldspar. *Nephelite,* p. 45.

L. In grains or masses, generally of a bright blue color. *Sodalite,* p. 46.

M. In masses, of a dark or yellowish green, easily scratched or cut by knife. *Serpentine,* p. 96.

N. In masses, often somewhat foliated. Greasy feel; very soft, marks cloth. White, greenish, gray. *Talc,* p. 97.

O. In hexagonal crystals, grains, or lumps. Dark smoky or bluish gray; translucent. Very hard, not scratched by quartz, garnet, or tourmaline. *Corundum,* p. 83.

P. In masses, compact or chalky. Friable, very soft, easily cut by finger nail. Rubbed between the fingers, has a soft soapy feel. *Kaolin,* p. 92.

TABLE 2

1 *A.* The mineral has a metallic luster or is opaque and gives a dark or strongly colored streak. 2.*
B. The mineral is without metallic luster or is transparent or translucent on very thin edges and its streak is white or light-colored. 6.*

2 *A.* Heated in the blowpipe flame, the mineral burns and gives off sulphurous fumes. Has a brass-yellow color. *Pyrite,* p. 90.
B. Heated in the reducing blowpipe flame, becomes magnetic when cold. Not brassy in appearance. Infusible or very difficultly so. Iron oxides. 3.

3 *A.* Is magnetic without heating. *Magnetite* (and in part *Ilmenite*), p. 85.
B. Is only magnetic after heating. 4.

4 *A.* Heated in the closed glass tube, gives water. *Limonite,* p. 89.
B. Gives little or no water. 5.

5 *A.* Reacts for titanium. *Ilmenite,* p. 86.
B. No reaction for titanium. Streak brownish or Indian red. *Hematite,* p. 90.

6 *A.* Fusible before the blowpipe (fusibility 1–5). 7.
B. Infusible or very difficultly fusible. 17.

7 *A.* Becomes magnetic after heating before the blowpipe in reducing flame. 8.
B. Does not become magnetic. 11.

8 *A.* Soluble in hydrochloric acid with separation of silica, sometimes gelatinous. 9.
B. Insoluble in hydrochloric acid or only slightly acted on. 10.

9 *A.* Micaceous or foliated. *Mica* (Biotite or Lepidomelane), p. 48.
B. Isometric crystals. Gelatinizes imperfectly. *Garnet* (Andradite), p. 67.
C. Gelatinizes. *Olivine,* rich in iron — *Fayalite,* p. 64.

10 *A.* Micaceous — difficultly fusible. *Biotite,* p. 48.
B. Isometric crystals or spherical in shape. After fusion gelatinizes with HCl. Dark red color. *Garnet* (Almandite), p. 67.
C. Quietly and difficultly fusible. Greenish black or bronze-brown. Good cleavage. *Pyroxene* (Hypersthene), p. 53.
D. Fuses with intumescence, coloring flame strong yellow. Black. Prismatic cleavage, angle 55 degrees. *Amphibole* (Arfvedsonite), p. 58.
E. Fuses quietly, coloring flame yellow. Black, prismatic cleavage, 93 degrees. *Pyroxene* (Ægirite), p. 53.

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* The appended number in each case refers to that in front of a succeeding section.

11

A. Readily and completely soluble in water; has a saline taste. *Halite,* rock salt, p. 109.

B. Difficultly soluble in water. After intense ignition, colors moistened turmeric paper brown.
  - *a.* Gives much water in closed glass tube, *Gypsum,* p. 106.
  - *b.* Gives little or no water in closed tube, *Anhydrite,* p. 108.

C. Soluble in hydrochloric acid without gelatinizing or separation of silica on evaporation. A drop of sulphuric acid in the solution precipitates calcium sulphate. *Apatite,* p. 91.

D. Soluble in hydrochloric acid with gelatinization.
  - *a.* Heated in closed glass tube, gives off water. 12.
  - *b.* Heated as above, yields little or no water. 13.

E. Soluble in hydrochloric acid, silica separates but no jelly forms.
  - *a.* Heated in closed glass tube, gives off water. 14.
  - *b.* Heated as above, yields little or no water. 15.

F. Insoluble in hydrochloric acid. 16.

12

A. Fuses quietly to a clear transparent glass. White or colorless; in slender crystals or fibrous bunches. *Natrolite,* see Zeolites, p. 99.

B. A fragment in warm dilute hydrochloric acid gives off minute bubbles of CO_2 gas. *Cancrinite,* see Feldspathoids, p. 47.

13

A. Fuses rather easily before the blowpipe, coloring the flame strong yellow. Dissolves easily in very dilute nitric acid and gelatinizes.
  - *a.* The nitric acid solution gives a precipitate with silver nitrate solution (p. 117). Color usually blue. *Sodalite,* p. 46.
  - *b.* The nitric acid solution gives a precipitate with barium chloride solution. *Hauynite-Noselite,* p. 47.
  - *c.* No reaction with silver nitrate or barium chloride. *Nephelite,* p. 45.

B. Difficultly soluble in hydrochloric acid and colors the flame very little. Has a good cleavage in two directions. *Anorthite,* see Feldspars, p. 33.

14

A. Usually in greenish masses, compact, greasy, sometimes fibrous. Difficultly fusible. *Serpentine,* p. 96.

B. Fuses quietly to a clear glass, coloring flame yellow. Generally in colorless or white garnet-like crystals. *Analcite,* p. 99.

C. Fuses with swelling and intumescence. Commonly in sheaf-like or radiated crystals. *Stilbite,* p. 99.

D. Fuses as in *C.* Crystals have a fine cleavage with pearly luster and lozenge-shaped section. *Heulandite,* p. 99.

15 *A.* Fuses quietly to a glassy globule. Slowly acted on by hydrochloric acid. Good cleavage in two directions; one generally shows fine parallel twinning lines. Often grayish or bluish with a play of colors. *Labradorite,* see Feldspars, p. 33.

B. Fuses quietly to white globule. Easily soluble in hydrochloric acid; solution evaporated to dryness, residue moistened with little hydrochloric and dissolved in water and filtered, ammonia produces little or no precipitate. *Wollastonite,* $CaSiO_3$, a variety of pyroxene, generally of a white color.

16 *A.* Micaceous. Cleaves into thin flexible elastic plates in one direction. *Micas,* p. 48.

B. Micaceous. Cleaves into thin plates, flexible but not elastic, micaceous. Very soft and has a greasy feel. Color white, gray, or greenish. *Talc,* p. 97.

C. Cleavable, micaceous, but cleavage plates not elastic, though flexible. Soft, but not so soft as talc. Color green, usually rather dark green. *Chlorite,* p. 94.

D. Not micaceous. Solid and brittle. Good cleavage in two directions at or about 90 degrees. Generally light-colored, red, or gray. Hard, cannot be scratched by knife. Difficultly fusible. *Feldspar,* p. 33.

E. Before the blowpipe, fuses with swelling and bubbling. Very hard, scratches feldspar. Generally in black columnar crystals, sometimes red or green. No cleavage. *Tourmaline,* p. 75.

F. Fuses quietly. Gelatinizes with hydrochloric acid after fusion. Crystals as on p. 67 or in spherical forms. Very hard. No good cleavage. *Garnet,* p. 67.

G. Fuses with swelling and intumescence to a black slaggy mass which gelatinizes in hydrochloric acid. Powdered mineral on intense heating in closed glass tube yields a little water. Yellowish to blackish green. *Epidote,* p. 70.

H. Fuses quietly or with little intumescence. Generally scratched by feldspar.

- *a.* Prismatic cleavage with angle of 87 degrees. *Pyroxene,* p. 53.
- *b.* Prismatic cleavage with angle of 55 degrees. *Amphibole,* p. 58.

I. Fuses with intumescence to a greenish or brownish glass which will gelatinize with hydrochloric acid. *Vesuvianite,* p. 72.

17
A. After intense ignition before the blowpipe, gives a brown stain when placed on moistened turmeric paper. 18.
B. Dissolves in hydrochloric acid but without gelatinizing or yielding a residue of silica on evaporation. 19.
C. *a.* Dissolves in hydrochloric acid and gelatinizes. *Olivine,* p. 64.
  b. Reacts for fluorine (see Topaz 22 *F*). *Chondrodite,* p. 79.
D. Dissolves in hydrochloric acid, does not gelatinize but silica separates. 20.
E. Insoluble in hydrochloric acid.
  a. Can be scratched by glass or a knife point. 21.
  b. Cannot be scratched by glass or the knife. 22.

18
A. Effervesces freely in *cold* dilute acid. *Calcite,* p. 101.
B. Effervesces freely in *hot* but not in cold acid, if not powdered. *Dolomite,* p. 104.

19
A. Heated in the reducing blowpipe flame, becomes magnetic.
  a. Little or no water in closed tube; streak brown-red. *Hematite,* p. 87.
  b. Water in closed glass tube; streak yellow-brown. *Limonite,* p. 89.
B. In hexagonal crystals usually. Gives reactions for phosphorus. A little dilute sulphuric acid gives a precipitate of white $CaSO_4$, in the cold concentrated solution of mineral in hydrochloric acid. Readily scratched by the knife. *Apatite,* p. 91.

20
A. Commonly in compact green masses. Sometimes fibrous, like asbestos, then white or brownish or yellowish. Greasy feeling, easily scratched by knife. *Serpentine,* p. 96.
B. In spherical or garnet-shaped crystals. White to gray. *Leucite,* p. 47.

21
A. *Micaceous.* Cleavage leaves tough and elastic. *Micas,* p. 48.
B. *Micaceous.* Cleavage leaves tough and flexible but not elastic. Intense ignition in closed tube gives water. Color green. *Chlorite,* p. 94.
C. *Very soft* and has a greasy feeling. *Talc,* p. 97.
D. Clay-like, compact or mealy. Leaves undissolved silica in the phosphorus salt bead. Gives water in the closed glass tube. *Kaolin,* p. 92.

22

A. Extremely hard. Scratches quartz. Generally has a parting that looks like cleavage. *Corundum,* p. 83.

B. No cleavage; conchoidal fracture. Scratches feldspar. Sometimes in hexagonal crystals with pyramid at end. *Quartz,* p. 80.

C. Prismatic cleavage. Becomes black before the blowpipe and very fine splinters fuse with difficulty. Brown to green or greenish black. *Pyroxene* (enstatite or hypersthene), p. 53.

D. Good cleavage in two directions at 90 degrees or nearly so. Generally light in color, red or gray. Scratched by quartz. Fusibility = 5. *Feldspars,* p. 33.

E. In prismatic crystals, often twinned; scratches quartz; red-brown to brownish black; intense ignition in closed tube gives a little water. *Staurolite,* p. 73.

F. Reaction for *fluorine* when heated in tube with sodium metaphosphate. With cobalt nitrate reacts for aluminum (see *G* below). One good cleavage. Scratches quartz. *Topaz,* p. 78.

G. Powdered mineral moistened with cobalt nitrate and intensely heated by the blowpipe on charcoal becomes blue (*aluminum*); *a,* in stout rectangular prisms, often full of impurities; not scratched by knife. *Andalusite,* p. 74; *b,* in bladed, generally blue, crystals; scratched by knife parallel to cleavage, but not at right angles to it. *Cyanite,* p. 74.

H. No crystal form or structure. Effervesces in Na_2CO_3 bead. Yields a little water in closed tube on intense ignition. *Opal,* etc., p. 82.

PART III

ROCKS

CHAPTER VI

GENERAL PETROLOGY OF IGNEOUS ROCKS

It has been previously stated that all rocks may be divided into three great natural groups: the igneous, the sedimentary, and the metamorphic. The *igneous* rocks are those that have been formed by the solidification of molten masses derived from within the Earth. On account of their origin they have at times been called the *primary* rocks, because the material that composes the other two classes has ultimately been derived from igneous rocks which, from time to time, have been formed either in or on the upper part of the Earth's crust. If we follow the view that the Earth was once molten, the original cooling crust must have been of the nature of igneous rock. Hence in this sense also the igneous rocks are the primary ones.

Distinguishing Characters of Igneous Rocks. The characters of the igneous rocks by which they may be distinguished from the sedimentary and metamorphic ones are of two kinds — field characters and specimen characters. The field characters are those that can only be observed in the field by studying the mass of rock in its relation to surrounding masses, or in other words its mode of occurrence, that is, whether it is a dike, a laccolith, a lava sheet, etc. These modes of occurrence will presently be described. If the mode of occurrence of a given rock mass can be clearly determined, it indicates, more definitely than anything else, whether or not the rock mass is igneous in origin.

It very often happens, however, that the boundaries of a rock mass are so covered or obscured that its relations to the surrounding rocks and its mode of occurrence cannot be observed, and it is often necessary to determine the nature of a specimen removed from a parent mass which is not accessible for study. We are then compelled to fall back upon those characters of the rock that are inherent and are to be observed by an examination of the material of the outcrop or specimen. Of these characters there are three principal ones that distinguish the igneous from the sedimentary and metamorphic rocks. They are:

a. Entire absence of fossils.
b. The material composition.
c. The arrangement of the material, texture, or structure.

The first character is an obvious one, but it is largely of negative value since many sedimentary and most metamorphic rocks do not contain fossils.

The second refers to whether the rock contains glass or is wholly made up of mineral grains, and if the latter, the kinds and relative amounts of the minerals present. If a rock is made up wholly or in part of glass it is certainly of igneous origin. The presence of certain minerals is also proof of igneous origin, but no general rule can be given by which, from its mineral composition, a rock can be definitely ascertained to be of igneous origin. This would have to be done from a knowledge of the different kinds of igneous rocks themselves, as they are described in a later chapter. The third character is that the igneous rocks present a homogeneous appearance: a surface of the rock in one direction is like a surface in any other direction; that is, they do not show the stratified, banded, or foliated structures that are characteristic of the sedimentary and metamorphic rocks. In addition there are certain minor structures which sometimes appear in igneous rocks, such as the amygdaloidal, which are highly characteristic and will be described later.

There are exceptions to the rules given above in *a* and *c*, but at the outset it is better for the student to consider them as if absolute, and the exceptions, which will be discussed in their appropriate places, will take care of themselves.

Occurrences of Igneous Rocks

There are two chief modes of occurrence of igneous rocks recognized by geologists, the *extrusive* and the *intrusive.* In the extrusive the molten mass or magma rising from depths below has attained the surface, come out upon it, solidified, and formed the rock. Rocks of this origin are also called *effusive* and sometimes *volcanic* rocks, though they are not always connected with volcanoes. In the intrusive rocks the magma has stopped before attaining the surface and has cooled and solidified, surrounded by other rock masses of the Earth's upper crust. Each of these groups has a number of recognized subdivisions, depending, in the extrusive rocks, on the conditions under which the magma was ejected, and in the intrusive rocks, on the relation that the mass bears to the rocks surrounding it. Following the course of the magma upward, we shall describe first the intrusive and then the extrusive modes of occurrence.

Intrusive Modes of Occurrence. These are *dikes, sheets, laccoliths, necks, stocks,* and *batholiths.* Various other modes have been recognized and described, but for simplicity's sake they may be regarded as modifications of these which have just been mentioned. The simplest form of intrusive masses is that of the dike, and this will be described first.

Dikes. A dike is the result of the simple filling of a fissure in rock masses by molten magma injected from below, and later solidified. In shape, its extension in length and breadth is great as compared with its thickness. It may " cut," that is, pass through, other igneous rocks or through sedimentary or metamorphic ones, whatever the material was in which the fissure was formed. In passing through sedimentary rocks it always cuts at some angle across the planes of stratification;

PLATE 2.

DIKE, CUTTING INTRUSIVE SHEET AND STRATIFIED BEDS, CASTLE MOUNTAIN, MONTANA.

(U. S. Geological Survey.)

if parallel to them it becomes an intrusive sheet. A dike may be of any size from a fraction of an inch in thickness up to half a mile; from two or three feet up to twenty are the ones most commonly observed; it may be but a yard or two long as exposed on the surface, or it may be many miles; a great dike in the north of England has been traced over a hundred miles. The plane of extension of a dike generally appears to be vertical or nearly so; often it is inclined at varying angles to the horizontal plane. This angle of inclination is called the *dip* of the dike, and the direction which its outcrop takes in intersecting the horizontal plane is called its *strike*, or *trend*. Dikes may have attained the Earth's surface and given rise to lava outflows, or they may have become exposed only by subsequent erosion. In the processes of erosion they may have resisted better than the surrounding rock and may therefore project as walls, a common feature; or they may have resisted less well and have become ditches, which is less common. Dikes very often show pronouncedly the columnar structure described later, the columns lying at right angles to the walls. Where dikes have cut through sedimentary rocks they have often changed and altered them for some distance in the manner described under contact metamorphism. A view of a dike cutting a sheet of igneous rock and stratified beds is seen in Plate 2.

Intrusive Sheets. It frequently happens, when molten magma is being forced upward through, or into, stratified rocks, that it attains a place where the conditions are such that it can most easily spread out in a layer between the sedimentary beds. This frequently happens where the beds are weak and easily penetrated, as in shales, thinly bedded sandstones, etc. The form of such a mass is like that of a dike, but unlike the latter it lies concordantly along the planes of stratification. Such sheets may be only a foot or less in thickness, and from this up to several hundred feet or even more; they may spread over many miles in extent. Like dikes, they often show a columnar structure, the columns being perpendicular to the upper and lower surfaces and thus often vertical. Sometimes they break, dike-like, across the strata and are continued along a new horizon. They are usually of the same hard, firm rock at top and bottom, and to some extent have altered and changed the sedimentary beds both above and below them. These characters distinguish them from surface flows of lavas which have later been buried by sediments deposited upon them. They are most likely to occur in connection with larger and more important intrusions of magma, such as stocks, laccoliths, etc., as accompanying or dependent features. In regions where thick, extensive sheets occur and the strata have been dislocated, faulted, and upturned, they often give rise, through erosion, to prominent topographic features, as illustrated in the trap ridges of southern New England, northern New Jersey, and in Scotland at Edinburgh, and in many other places. An intrusive sheet is now generally called a *sill*. Examples are shown on Plates 2 and 3.

Laccoliths. These are great lenticular masses of igneous rock lying between stratified beds that wrap around them. If in the forming of an intrusive sheet the magma is supplied from below faster than it can spread at a given thickness laterally, the strata above will begin to arch up, and if the process continues, a great thick half lens of liquid rock will be formed.* A cross section of such a one is shown in Fig. 63. They commonly run out into intrusive sheets or are accompanied by them. Also where the folding strata on the flanks of rising mountain ranges are subjected to horizontal pressure, they may tend to open, and such openings may be filled with magma from below, *pari passu* with their opening, as illus-

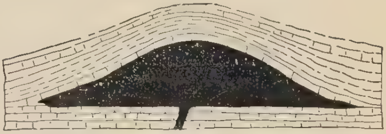

Fig. 63. Cross Section of a Laccolith

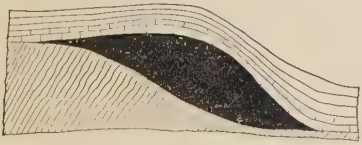

Fig. 64. Section of an Inclined Laccolith

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* Increased viscosity of magma also helps in this result.

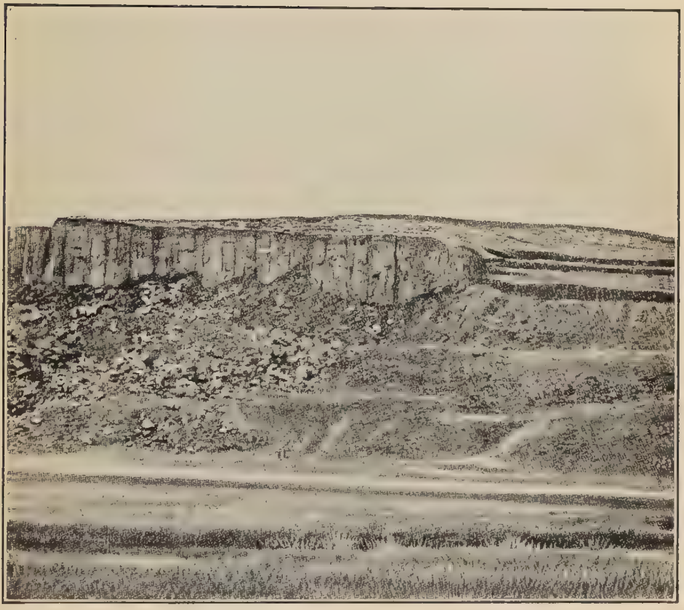
trated in Fig. 64. In general, laccoliths are more or less circular or oval in ground plan, and while many are symmetrical as in the diagrams, they are likely to be more or less distorted in shape. The floor may be flat or tilted as in the figures. In many of the larger laccoliths the floor dips from the perimeter inward toward a point under the center of the laccolith, just as if the floor had sagged from loss of support. Such loss of support is conceivably due to the emptying of a magma reservoir below the laccolith. The immense Duluth laccolith of Minnesota is a notable example of a laccolith having a centripetally dipping floor.

Laccoliths differ from intrusive sheets only in being extremely thick in comparison with their lateral extension, and all gradations between the two occur. A laccolith may be a mile or more in thickness and a number of miles in diameter, or but a few hundred yards across. The beds above are usually stretched, thinned, and broken in the process of formation. Like intrusive sheets, laccoliths alter the strata above and below them by contact metamorphism. They occur most commonly in weak beds of shale, etc., the stronger, thicker beds of sandstone and limestone being up-arched. The best examples that are known are in the region of the Rocky Mountains, where in many places they are not uncommon.

Laccoliths have been described in which the roof has been ruptured and driven upward by the magma rising like a plug through the strata. It has been suggested that such forms be called *bysmaliths* (Greek, plug rocks). It has also been suggested that when a body of magma is injected into the stratified rocks like a laccolith, but of indefinite shape and without the relations to the planes of stratification which a laccolith has, such a mass be termed a *chonolith* (Greek, mold — used in casting — rock).

Necks. When a volcano ceases its activity and becomes extinct, the column of magma occupying the conduit leading to unknown depths below may solidify and form a mass of igneous rock. Erosion may cut away a great part of the light porous ashes and lavas, leaving this more solid and resistant rock projecting, as shown by the heavy line *abc* in Fig. 65. Or the level of erosion may continue to descend into the rocks

PLATE 3.



LACCOLITH, AND INTRUSIVE SHEETS OF BASALT, IN SANDSTONES, SHONKIN SAG, MONTANA.

(U. S. Geological Survey.)

that form the basement on which the volcano is built, all traces of the ashes, lavas, etc., being swept away and only this mass being left to mark the former site of the volcano. Such a mass of rock is known as a volcanic *neck*. It is commonly more or less circular in ground plan and may be from a few hundred yards up to a mile or more in diameter. The rocks about it are generally fissured and filled with dikes and, if stratified, contain intrusive sheets.

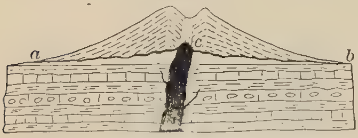


Fig. 65. Section Through a Volcano

Stocks. This term has been applied to large bodies of intrusive rock which in the form of magma have ascended into the upper region of the Earth's crust and there solidified. They have become visible by extended erosion and tend to have a more or less circular or elliptic ground plan. Their plane of contact cuts across the inclosing rocks and is more or less irregular, and the mass may widen in extent as it descends. Their areal extent may be anything from a few hundred square yards to many square miles. Since they are likely to form protuberant topographic features through erosion they are sometimes, especially in Great Britain, called *bosses*, if of circular ground plan. The distinction from a volcanic neck is not one of size alone, though necks tend to be smaller than stocks, but lies in the fact that the term neck is employed only when there is evidence that there has been extrusive volcanic activity from the column of magma that has formed the rock mass. Some stocks were doubtless necks, but this cannot now be proved. The granite hills of New England, of Scotland, and of other old eroded mountain regions are mostly stocks or bosses.

under 40 mls

Batholiths*. This term is used to designate those huge masses of igneous rock which are intrusive into the sedimentary and metamorphic rocks. They are seen in deeply eroded

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* By some writers spelled *bathyliths*.

PLATE 4.

SQUARE BUTTE, A DENUDED LACCOLITH, HIGHWOOD MOUNTAINS, MONTANA.
(U. S. Geological Survey.)

areas of the Earth's crust, where they are characteristically accompanied or surrounded by metamorphic rocks, as in eastern Canada, or in mountainous regions where they form the central cores or masses of the ranges, as in the Alps or in the Sierra Nevada. They differ from stocks only in their much greater size, as they are not infrequently many thousands of square miles in surface area. It has been suggested that masses less than 100 square kilometers (40 square miles) in areal extent be called stocks, and those larger than 100 square kilometers be called batholiths.

While some stocks have clearly displaced the rocks whose site they occupy, the mode of emplacement of others and of batholiths is still a problem to be solved. Some have held that they have made room for themselves in the Earth's crust by melting and assimilating the rocks that formerly occupied the space now occupied by the igneous mass, while others have urged the view that the invading magma has actively made room for itself by crowding aside the circumjacent rocks. Various modifications of these views have been suggested, but geologic science is not yet in a position to pronounce definitely upon their correctness.

Extrusive Igneous Rocks. For petrographical purposes two chief modes of extrusion may be recognized: the *quiet* one, giving rise to outwellings of magma in the liquid state which then solidifies to rock; and the *explosive*, in which the material, by the violent action of gases, is projected into the air and falls in a solid but fragmental form.

Quiet Eruption; Lava Flows. When the magma rises to the Earth's surface and outpours it is then called *lava*. The solidified material is often called a sheet of lava or *extrusive* sheet. Such flows often come from volcanoes, the extrusions of some, like those now active in Hawaii, being chiefly of this nature; while in others they alternate with or succeed explosive projections of fragmental material. Some lava flows are not connected with volcanic eruptions but have taken place as quiet outwellings from numerous fissures. This has occurred at various times in the Earth's history on a huge scale, as in the Columbia River region of the northwestern United States and in western India. In these regions the series of superposed lava flows are thousands of feet in thickness and cover areas of more than 200,000 square miles.

Not infrequently sheets of lava have sunk below sea-level and been covered by deposits, or they have originated on the sea floor and have been covered. Such buried extrusive sheets are distinguished from intrusive ones by the fact that they have not altered or changed the sediments above them by contact metamorphism (*q. v.*), and their upper surfaces usually show the structures common to the surface of lavas, such as the vesicular, amygdaloidal, scoriaceous, and ropy ones described later.

Explosive Eruption; Tuffs and Breccias. When a magma attains the surface in the canal of a volcano it may give rise to quiet flows of lavas as mentioned above, or, if its viscosity is sufficient and it is charged with vapors under great tension, it will give rise to explosive activity, and the liquid material will be projected into the air, finally to fall in solid fragmental form. Owing to the expansion of the vapors, chiefly steam, the projected pieces usually have a more or less pronounced vesicular structure, and vary in size from those weighing perhaps several hundred pounds to dust so fine that it floats for long periods in the air. According to size the projected material may be roughly classified as follows: Pieces the size of an apple and upward are called *volcanic bombs;* those the size of nuts are termed *lapilli;* those the size of small peas or shot *volcanic ashes;* while the finest is *volcanic dust.* The coarser material, the bombs, ashes, and lapilli, falls around the vent

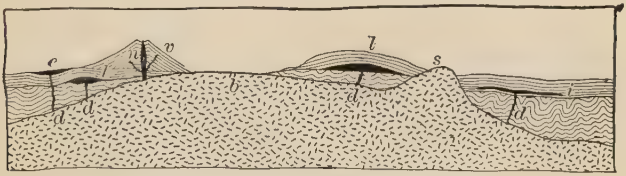

Fig. 66. Diagram to Illustrate the Occurrence of Igneous Rocks: *b*, **batholith;** *s*, **stock;** *n*, **volcanic neck forming** *v*, **a volcano with tuffs and breccias;** *l*, *l*, **laccoliths;** *i*, **intrusive sheet;** *e*, **extrusive sheet;** *d*, *d*, **dikes. Horizontal distance shown, thirty miles; vertical distance, three miles.**

and builds up the cone; the lighter ashes and dust, carried by air currents, tend to fall after these and at greater distances. The beds of coarser material thus produced are termed *volcanic breccias*, while the finer are known as *tuffs*.*

General Characters of Igneous Rocks

Since igneous rocks are formed by the consolidation of magmas, manifestly the nature of the resultant rock must largely depend on the chemical composition of the magma from which it was formed, for most rocks are composed of mineral grains, and the kinds and relative amounts of these minerals must depend on the kinds and relative amounts of the chemical elements that form the molten fluid. It is pertinent, therefore, to inquire what the chemical character of the Earth's magmas is and if any general rules appear to govern their composition.

Chemical Composition of Magmas. We cannot, of course, subject a magma directly to investigation, but this may be essentially done if an average sample of an igneous rock is subjected to chemical analysis. Several thousand such analyses have been made of rocks from all parts of the world, and these analyses show that the rocks, and therefore the magmas, are made up of a few chemical constituents, which are reported by the chemist in terms of the following oxides: *silica*, SiO_2; *alumina*, Al_2O_3; iron oxides, both *ferric*, Fe_2O_3, and *ferrous*, FeO; *magnesia*, MgO; *lime*, CaO; *soda*, Na_2O; and *potassa*, K_2O. Other oxides, including water, are also reported but in such relatively small amounts that they may be neglected. As will be shown later, however, the water and other volatile constituents are of great importance while in the magma.

The variation in the chemical composition of magmas is shown in a general way in the following table of analyses. Although it is conventional to report chemical analyses in terms of oxides, it must not be thought that these oxides thus re-

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* Volcanic tuff was formerly commonly called *volcanic tufa*, but at the present time it is customary to restrict the word *tufa* to deposits from aqueous solution, especially those of a calcareous nature.

ported exist as such in the magma; in reality they occur in the magma in combination as mineral molecules, more or less electrolytically dissociated.

	I	II	III	IV	V	VI	VII	VIII
SiO_2.....	56.6	65.5	72.5	65.1	56.0	49.2	40.1	38.4
Al_2O_3....	22.4	17.8	13.1	16.2	15.6	12.0	7.8	0.3
Fe_2O_3....	1.8	0.7	1.7	1.1	1.2	2.8	7.3	3.4
FeO.....	0.8	1.2	1.0	3.2	6.3	8.8	8.6	6.7
MgO....	1.3	1.0	0.6	2.3	6.8	9.3	23.7	45.2
CaO.....	0.3	1.9	1.0	4.0	7.3	10.6	6.5	0.4
Na_2O....	8.5	5.6	4.2	4.0	2.2	1.9	1.2	0.1
K_2O.....	7.3	5.6	4.9	2.5	1.3	1.7	0.5	
Rest.....	1.4	0.7	0.7	1.6	3.3	3.2	4.5	5.7
Total..	100.4	100.0	99.7	100.0	100.0	99.5	100.2	100.2

I, Nephelite Syenite, Serra de Monchique, Portugal; II, Syenite, Highwood Mountains, Montana; III, Granite, Castle Mountains, Montana; IV, Quartz Diorite, Electric Peak, Yellowstone Park; V, Diorite, Montgomery County, Maryland; VI, Gabbro, Red Mountains, Montana; VII, Peridotite, Devonshire, England; VIII, Dunite, Tulameen River, British Columbia.

Variation of Magmas and Mineral Composition. It is not to be understood that all the different varieties of magmas are represented by these analyses; they are selected to show only the most prominent features of variation. Certain of these features are readily apparent. Thus in the first three analyses it is evident that silica, alumina, and the alkalies, potassa and soda, are the chief oxides that make up the constituents of the magmas, while lime, iron, and magnesia play a very minor part. Therefore, if such magmas should crystallize into minerals, these minerals would be chiefly alkalic feldspars, because the alkalic feldspars are composed of silica, alumina, and alkalies. Again, if we regard the amounts of silica in these three analyses and recall that orthoclase, the potassium feldspar, contains 65 per cent of silica, and albite, the sodium feldspar, about 68, it is clear that in No. III there is more silica than needed to form the alkalies and alumina into feldspars, and there will therefore be extra silica which will crystallize as free quartz. In No. I, on the contrary, there is not enough silica to turn all of the alumina and alkalies into feldspar, and a certain amount of some mineral, such as nephelite, which contains these oxides in combination with a smaller amount of silica, must be formed to compensate this deficiency. In No. II the per cent of silica is very nearly that required for the pure feldspars, and these will make up the great bulk of the rock with little either of quartz on the one hand, or of nephelite on the other.

If now we turn our attention to the oxides of calcium, iron, and magnesium, it is evident that the minerals which they produce, such as biotite, hornblende, and pyroxene, will have but a subordinate rôle in the first three rocks, but in Nos. IV–IX these oxides continually increase while silica, alumina, and alkalies also decrease, and eventually the last two vanish and the silica becomes very low. Expressing this in terms of minerals, if the magmas crystallized, it is evident that in these four the *ferromagnesian* minerals — those containing iron or magnesium or more commonly both — such as pyroxene, amphibole, or olivine, would play an increasingly important rôle, and that the last rock would be wholly composed of them, while feldspars would correspondingly become less important and ultimately disappear.

In this connection the variation of lime deserves a separate word because lime has a dual function: it may form a feldspar with alumina and silica, which then commonly combines with soda feldspar to form plagioclase (soda-lime feldspar); or it may enter into the ferromagnesian minerals, pyroxene and amphibole. It generally does both; and thus for a time, as we follow the table of analyses from left to right, as lime increases, the quantity both of plagioclase and of ferromagnesian minerals increases also. Coincident with this the alumina also increases somewhat.

Variation shown by Diagrams. The facts that have been stated above may be shown in a graphic manner by means of a simple diagram, Fig. 67. Thus in the place of the analyses of the foregoing table we may draw vertical lines, one for each analysis, at equal distances apart and on each line set off a vertical distance in millimeters equal to the per cents of each oxide in the analysis. Through these points lines are drawn corresponding to each oxide, the iron and magnesia, from the similarity of function they exhibit, being united in one line. The equal distances for each analysis at the foot of the diagram thus serve as abscissas and the percentages are ordinates, while the connecting lines approach curves which show the mutual relations of the oxides. In the description of the variation of the oxides it was pointed out that this caused a corresponding variation in the minerals produced by the crystallization of the magmas composed of these oxides. By considering the relative amounts of the important minerals which each type of analysis would produce, we can construct a diagram, Fig. 68, which will show the variation of the minerals in a general way in the common rocks. It also shows the relative proportions of the minerals in the more common and important kinds of igneous rocks, and it serves as a basis for their classification, as will be explained later. The relative proportions of the minerals are given in the vertical direction, the variation and passage of one kind of rock into another in the horizontal direction.

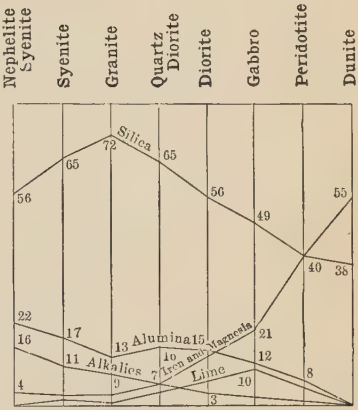


Fig. 67. Diagram to Illustrate Chemical Variation of Igneous Rocks

It should be repeated that these diagrams and the table of analyses are not to be taken in a hard and fast manner as representing the limits of variation and all the possible mineral combinations of igneous rocks. This would be very wide of the truth. Other analyses might be selected which would yield different diagrams, and if of rare and uncommon rocks, they might be very different indeed, but in a general way these may be accepted as showing the more important chemical and mineralogical features that distinguish the common kinds of igneous rocks from one another.

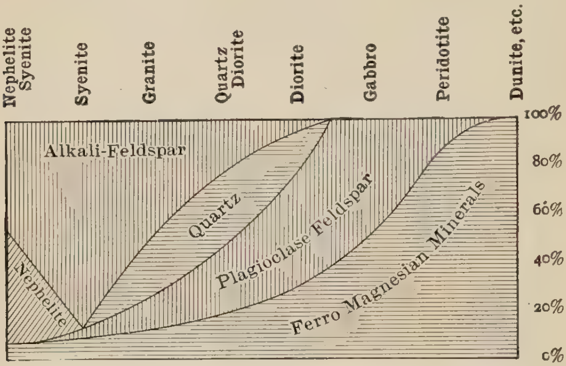


Fig. 68. Diagram to Illustrate the Variations and Relative Proportions of the Minerals Composing the Important Igneous Rocks

Minerals of Igneous Rocks. From what has been stated in the foregoing sections it is evident that the more important minerals that compose the igneous rocks are the feldspars, quartz, and the ferromagnesian group. For purposes of classification, to be explained later, it is convenient to contrast the ferromagnesian on the one hand with the quartz and feldspars on the other. Recalling that silica (SiO_2) and alumina (Al_2O_3) are prominent substances in the composition of these latter minerals, and following American petrographic usage, we may term this group the *sa*lic one. More specifically, the prominent minerals of the igneous rocks are given in the following table:

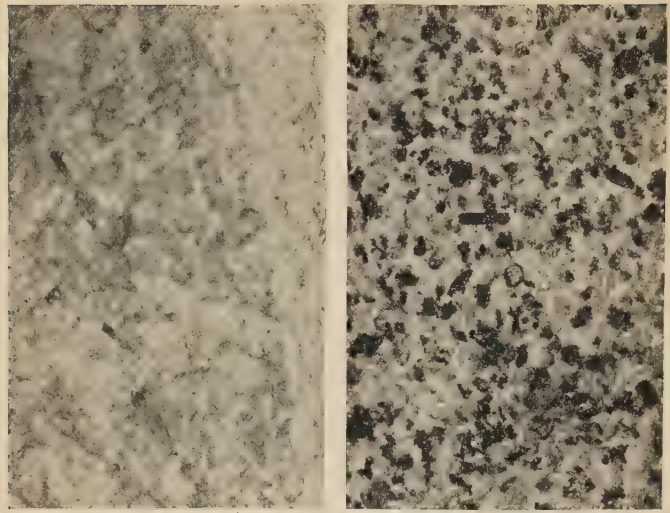
Salic Group	Ferromagnesian Group
Alkalic Feldspar	Pyroxenes
Plagioclase Feldspar	Amphiboles
Quartz	Biotite
	Olivine
Nephelite	
Sodalite	Iron Ores
Corundum	

The last three in the salic group are of much less importance than the first three on account of their restricted occurrence; the iron ores, hematite, ilmenite, and magnetite, though so widely distributed that nearly all igneous rocks contain one or more of them, are of less importance than the other ferromagnesian minerals because they usually form only a very small proportion of all the minerals in the rocks. A mineral, like these, which may be quite evenly distributed through a rock but makes only a small part of its mass, is called an *accessory component* in contradistinction to those which form its main bulk and are termed *chief or essential components*.

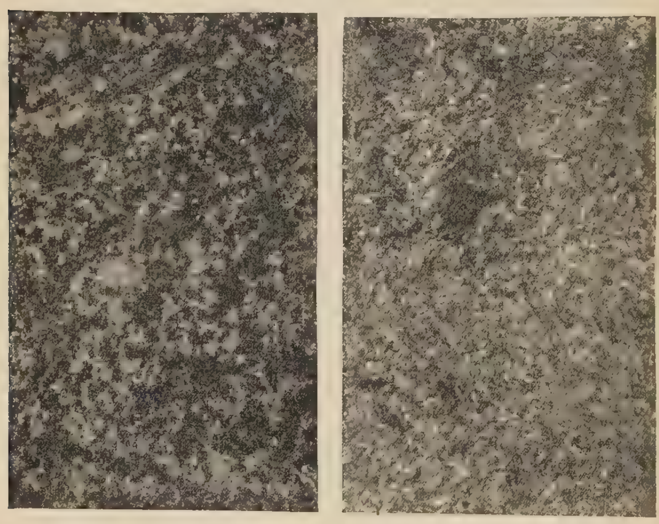
The chemical and physical characters of the minerals mentioned in the above list have been described under their appropriate headings in Part II, to which reference may be made for further information concerning them.

Order of Crystallization. If a polished surface of a coarse-grained rock be attentively studied with a lens, or better if a thin section be observed under the microscope, it will usually be found that there are more or less distinct evidences that all the minerals composing it have not crystallized simultaneously but successively. Thus in Fig. 69 grains and octahedrons of magnetite are inclosed in the crystals of biotite mica (M); they occur also in the other minerals. They are evidently older than the mica because they are inclosed by it. The mica is older than the soda-lime feldspars or plagioclases (P) because it abuts into them with its own crystal faces or is partly inclosed by them as they grow around the already formed crystals. In the same way the plagioclase has its own form where it adjoins the alkali feldspar, orthoclase (O) and the

PLATE 5.



A. Anorthosite, all Feldspar. B. Syenite, mostly Feldspar.



C. Diorite, some Feldspar. D. Peridotite, no Feldspar.

CONTRAST OF FELDSPATHIC AND FERROMAGNESIAN ROCKS.

quartz (Q), which surround it, and is therefore judged to be older than they are. When the orthoclase and quartz are considered they do not show any crystal boundaries with respect to one another, and their crystallization is therefore judged to be more nearly simultaneous. The order of crystallization as thus worked out in this particular case is: first, magnetite, then biotite mica, then plagioclase, and lastly orthoclase and quartz.

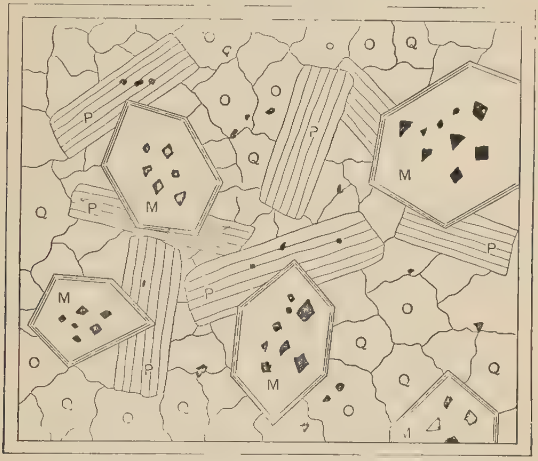
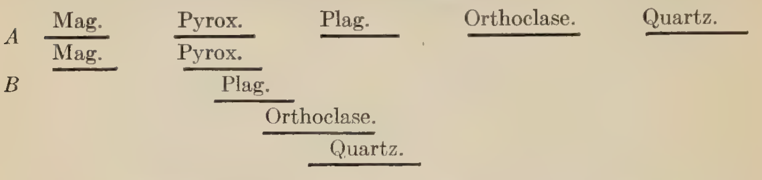


Fig. 69. Diagram to Illustrate Successive Crystallization

The studies that have been made of igneous rocks teach that in general the order of crystallization is: first, the oxides of iron, then ferromagnesian minerals, then plagioclase feldspars, then alkalic feldspars (and feldspathoids), and lastly quartz. One observes from this, as illustrated in the adjoining table, that the process begins with metallic oxides which contain no silica, that next come the ferromagnesian minerals, ortho and metasilicates, then feldspars which contain more silica, and finally quartz or

1. Magnetite, Fe_3O_4.
2. Pyroxene, $(Mg,Fe)Ca(SiO_3)_2$.
3. Plagioclase, $\left\{\begin{array}{l} mCaAl_2Si_2O_8. \\ nNaAlSi_3O_8. \end{array}\right.$
4. Orthoclase, $KAlSi_3O_8$.
5. Quartz, SiO_2.

free silica. Thus there tend to crystallize out successively minerals richer and richer in silica. It is not to be understood, however, that one mineral necessarily finishes its period of crystallization before another one begins as in A, but rather



that they overlap as in B, that is, that one may begin before another has finished, and continue after the former has ceased. Experience shows that with orthoclase and quartz the overlap is so great that they crystallize nearly simultaneously, only orthoclase usually begins and quartz finishes.

Insolubility vs. Infusibility. A molten silicate magma is to be regarded as a complex solution of some compounds in others, like a solution of several salts in a solvent, such as water. As the heated solution cools, a point is reached where some compound, or mineral, becomes insoluble in the cooling solution and it therefore crystallizes out. The statement that is sometimes made that the minerals crystallize in the order of their fusibility is essentially wrong; for in the preceding paragraph we saw that pyroxene crystallizes before quartz, yet pyroxene is rather readily fusible before the blowpipe, while quartz is infusible. It is not therefore the infusibility but the solubility that determines the order of crystallization.

Influence of Mineralizers. Experience teaches us that those magmas which attain the surface in volcanoes and in lava flows contain large quantities of volatile substances, especially water vapor, which they give off, frequently with explosive violence. It was formerly considered that the magmas imbibed these from the moisture-laden rocks with which they came in contact on their way to the surface. At present these volatile substances are generally held to be wholly or in large part of magmatic origin, that is, original constituents of the

Earth's interior molten masses, contained therein under pressure. Without further regard to the theories advanced to explain their presence, we know that the magmas contain them and that they are of great importance in a number of ways in the formation of igneous rocks. The most important of these volatile substances is water vapor, but carbon dioxide, fluorine, boric acid, sulphur, and chlorine are also prominent and may produce important results. The work of various investigators, especially the French, has shown that, while some minerals, such as pyroxene, magnetite, calcium feldspar, olivine, and nephelite, may be artificially produced by fusing their constituents together and allowing the molten mass to cool slowly, other minerals, such as hornblende, biotite, orthoclase, and quartz, do not form in dry fusions in the same way. For their production more or less of the volatile substances mentioned above must be present, especially water vapor. These substances act in three ways: first, in a chemical manner, since some minerals, such as biotite and hornblende, always contain small quantities of water (in the form of hydroxyl, —OH) or fluorine or both, and these are consequently necessary for their production; second, in a physical manner, in that these substances lower the melting point of the magma; and thirdly, they greatly increase its fluidity. Thus orthoclase, albite, and quartz, which have extremely high melting points, in a dry fusion become so viscous on cooling that they are unable to crystallize and therefore they solidify as glasses. The addition of water under pressure lowers the temperature of solidification and increases the fluidity or mobility of the melted mass, permitting such free movement of the molecules that they can arrange themselves in crystal form, and thus produce the above minerals. These substances then, such as water, fluorine, etc., which exert so important a function in processes of crystallization and in the formation of igneous rocks, are called *mineralizers*. As crystallization progresses, all of these substances, except the quantity that is chemically (and to some extent mechanically) retained in the minerals, are gradually excluded from the solidifying rock mass to play an active rôle in new and important processes, such as the formation of pegmatites, contact metamorphism, and others which will be described later in their appropriate places.

Texture of Igneous Rocks

to here for

It has been pointed out that igneous rocks vary in the kinds and proportions of the minerals that compose them and that this variance is mainly due to the chemical composition of the magmas from which they are derived. Another important way in which these rocks vary is in their *texture.* Thus one rock may be made up of mineral grains so large that the different minerals are easily distinguished, while in another the grains are so small as to defy identification by the eye or simple lens. Again, almost all the grains may be of about one size, or they may vary in size, some being relatively large while the rest are minute. Or again, the conditions may have been such that the magma had no opportunity to crystallize but solidified as a simple glass, or only partly crystallized and formed a mixture of glass and crystals. Such variations for the most part are independent of chemical composition; they depend upon the *physical conditions* under which the molten mass has solidified, and thus a magma of a given composition may appear in any one of the states mentioned above if subjected to the proper conditions.

The characteristic features which a rock exhibits in this respect constitute its *texture,* and rocks are distinguished and classified in one way according to their textures, just as in another way they are distinguished and classified according to their mineral composition.

Factors determining Texture. If a strong hot solution of a salt, such as common alum in water, is allowed to cool very slowly and regularly, comparatively few centers of crystallization will be set up, and the few resulting crystals will have a long period of growth and will be of good size. If, on the contrary, the cooling is very rapid, a great number of centers of crystallization will form, the period of growth will be short, and a great number of very small crystals will result. The same is true in the molten liquids from which the igneous rocks are formed. If the cooling progresses with great slowness and regularity, then coarse-grained rocks are produced; if the cooling is rapid, fine-grained rocks are formed; and if the cooling takes place so quickly that there is no opportunity for complete crystallization, rocks wholly or in part composed of glass will result. The *rate of cooling* then is a prominent, and in fact the most prominent, factor in the production of rock texture. In addition to the temperature, there has been a tendency in the past to ascribe also a prominent rôle to the *pressure.* The idea involved is that if a magma remains liquid within the Earth at a given temperature, and if for any reason the pressure increases, a point will be eventually reached where the magma will be forced to crystallize and become solid, since in so doing its volume would be reduced. Decrease of temperature and increase of pressure would then work together. While this may be true in theory it does not seem probable that the pressures obtaining in the upper region of the crust are a very prominent factor in this direction, since geological observation has shown that a particular variety of texture can be found unchanged through a range of 10,000 feet vertically. Still, it cannot be denied that pressure probably has some influence on the process of crystallization and the production of rock texture.

The *presence of mineralizers*, especially water, has undoubtedly a strong influence on the texture, particularly in the siliceous rocks, for this greatly increases the fluidity of such magmas and, as they cool down and the crystallizing points of the different minerals are reached, they still retain their mobility instead of becoming stiffly viscous. This increases the range of movement of the mineral molecules in process of formation, and enables larger crystals to grow and a coarser texture to be produced. As we shall see later, this effect reaches its maximum in the pegmatite dikes.

In connection with what has just been stated, *chemical* *composition* of the magmas has a certain influence in producing texture. This shows itself in two ways. Those magmas which are deficient in silica, and especially those which contain much iron and magnesia and which are shown in the right-hand side of the diagrams given on a previous page, remain liquid, without becoming stiffly viscous, to much lower temperatures than those with high silica, which are found expressed in the middle of the diagrams. This liquid condition enables them to crystallize more freely and to form in consequence coarse-textured rocks under circumstances in which the siliceous magmas would produce only types fine-grained in texture or even glassy from inability to crystallize completely, owing to increasing viscosity. The other way in which chemical composition influences texture is as follows. Differences in composition in the magmas mean, of course, differences in the kinds of minerals which they produce. Different minerals crystallize in different shapes and although, owing to interference with one another, they may not form in perfect crystals, they tend to take such shapes. Some form tabular shapes, others spherical or cuboidal grains or elongated prisms. Thus, while the general size of such grains may remain the same throughout a mass of rock, such differences in shape will produce corresponding differences in what we may call the pattern or *fabric* of the rock and thus influence its texture.

Relation of Texture to Geologic Mode of Occurrence. It is evident that the conditions most favorable for the production of coarse-textured rocks — conditions described in the preceding discussion as slow cooling, pressure, and the presence of mineralizers — will, in general, be best realized when the magma is in large mass and deeply buried in the Earth's crust so that it is completely enveloped by surrounding rock masses. The heavy cover retains the heat and the mineralizers and gives in part the pressure. Such igneous rocks, formed in depth, will only become exposed to our observation when continued erosion has carried away the superincumbent material. They are often therefore called *plutonic* or *abyssal* and sometimes *massive* rocks, and, referring to what has been said of the modes of occurrence of the igneous rocks, it can be seen that batholiths, stocks, and the lower part of volcanic necks may be particularly expected to exhibit such texture, and as a matter of fact they nearly always do so.

On the other hand, when the magmas attain the surface and are forced out in volcanic eruptions, lava flows, etc., entirely different conditions will prevail: there is no cover to retain the heat and the cooling in consequence is rapid. Also, the pressure has been relieved, and with loss of cover and pressure the mineralizers quickly depart. As a result, fine-grained textures are formed, or the cooling may be so rapid that crystallization may fail to occur, either wholly or in part, and rocks entirely or partly composed of glass may be produced. When rocks are more or less glassy it is, in general, very good evidence that they solidified as surface lavas.

In the smaller intrusive bodies, such as the dikes, sheets, and laccoliths, the conditions in general are between the two sets just described. The volume relative to the surrounding rocks is less, the loss of heat and mineralizers more rapid than in the stocks and batholiths, and, since in general the depth is less, the pressure is diminished. Thus the textures are usually between those of the larger abyssal masses and the effusive lavas. But the conditions in these occurrences tend to be very variable, and in accord with this we find the textures sometimes aphanitic like those of the effusives — but very rarely glassy — and sometimes coarse-granular like the textures of the larger abyssal masses. Moreover, in the smaller intrusive bodies the function of chemical composition described in the preceding section is often most strongly displayed. Thus highly siliceous dikes and sheets of fine grain will be found associated under the same geological conditions with other ones low in silica and high in iron and magnesia of relatively much coarser grain.

It is especially in these occurrences and in the surface lavas that the *porphyritic texture*, to be presently described, is most likely to be found.

Textures of Igneous Rocks. Based on the principles that have been enunciated in the foregoing sections, the textures of igneous rocks for megascopic study may be classified as follows:

Grained. All sizes of grain large enough to be seen with the unaided eye. *Example,* ordinary granite.

Aphanitic. The rock is crystalline, i.e., not glassy, but the grains are too fine to be perceived by the eye. *Example,* many felsites.

Glassy. The rock can be distinctly seen to be wholly or in part composed of glass. *Example,* obsidian.

The distinctions stated above relate in part to the *crystallinity,* or degree of crystallization, of the rock, for all grades of transition between rocks composed wholly of glass, partly of glass and partly of crystals, and wholly of crystals exist, though to be perceived by the unaided eye the glass must form a great or the greater part of the rock. These distinctions relate also in part to the absolute sizes of the crystal grains, or what we may term the *granularity.*

The grained, or phanerocrystalline (Greek, φαγερός, visible), rocks can be divided according to the size of grain as follows: (See Figs. 1, 2 and 3, Plate 6.)

Fine-grained, the average size of the particles less than 1 millimeter or as fine as fine shot.

Medium-grained, between 1 and 5 millimeters.

Coarse-grained, greater than 5 millimeters or as great as or greater than peas.

But another very important feature of texture is that of the pattern or *fabric* and this, for megascopic work, is chiefly due to the *relative sizes* of the crystal grains in a given rock. There are two chief kinds of fabric which may be distinguished:

Even-granular fabric (or texture), all grains are of approximately the same general size.

Porphyritic fabric (or texture), some grains are of a larger size and contrast with the finer ones or with the glass in which they are inclosed.

Even-granular Texture. While this means that in a given rock the crystal grains have approximately the same general size, as may be seen by referring to Plate 6, it does not mean that they have necessarily the same shape. Careful examination of granites which have this texture will show that the dark mica is generally present in well-formed hexagonal tablets or crystals, while the feldspars and quartz are in shapeless masses, or the feldspar tends to have rough tabular or brick-like shapes. This difference in crystal development depends on the order of crystallization, as previously explained.

Porphyritic Texture. Porphyry. In this texture, when typically developed, there is a sharp contrast between larger crystals that have definite crystallographic bounding faces, which are termed *phenocrysts* (Greek, *φαίνειν*, to show), and the material in which they lie embedded, called the *groundmass*. This groundmass may have the textural characters described on a preceding page; it may be even-granular, coarse or fine, it may be aphanitic, or wholly or partly glassy. A rock with this textural fabric is called a *porphyry*.* Examples are shown in Plate 7.

Great variations are seen in the phenocrysts. They may be extremely numerous and the amount of groundmass small, or the reverse; they may be an inch or more in diameter or they may be so small as to require close observation to detect them; they may be of light-colored feldspars and quartz or dark-colored ferromagnesian minerals (hornblende, augite, and pyroxene) or of both kinds of minerals. Again, they may be extremely well crystallized and afford such striking specimens

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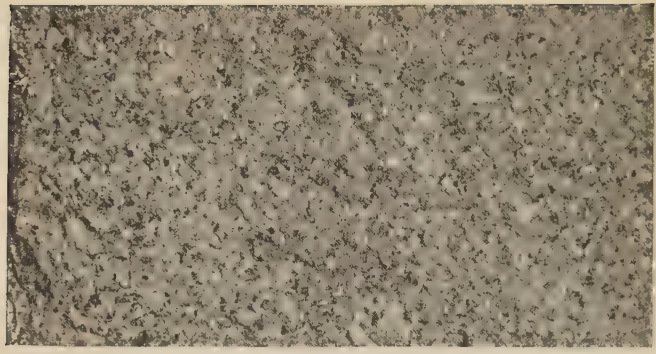
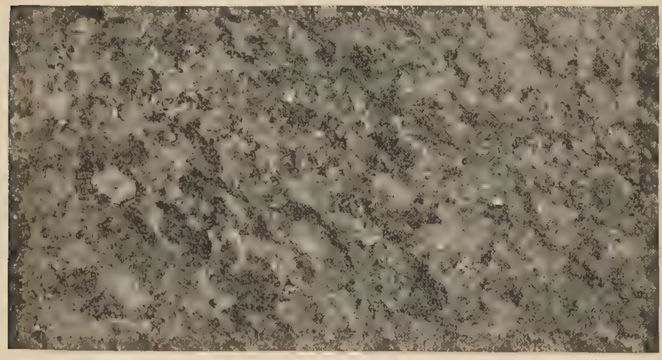
* The porphyritic texture is not a contrast of *colors* of mineral grains but of *sizes*. Care must be taken, therefore, not to confuse, for instance, a white rock consisting of grains of light-colored minerals such as feldspar, in which are embedded a few conspicuous black grains of a ferromagnesian mineral of the same size, such as hornblende, with a porphyry.

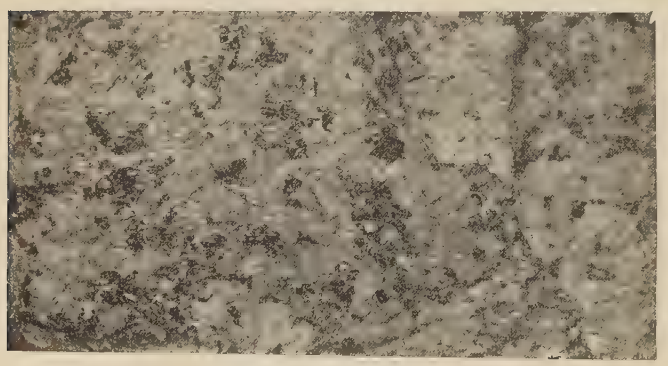
PLATE 6.



1. Fine Grain.



2. Medium Grain.



3. Coarse Grain.

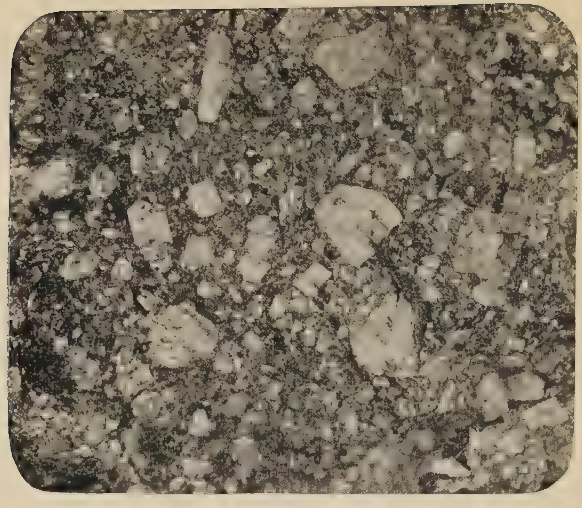
EVEN-GRANULAR TEXTURE.

of perfect crystal development that they find a place in mineral cabinets or they may be very poorly defined in crystal form. And with increase in numbers and poor crystal form, all degrees of transition into the even-granular texture may be found. The porphyritic texture is extremely common in lavas and in intrusives of small mass, such as dikes, sheets, and laccoliths; it is rarer in the abyssal rocks, but is sometimes seen, especially in granites.

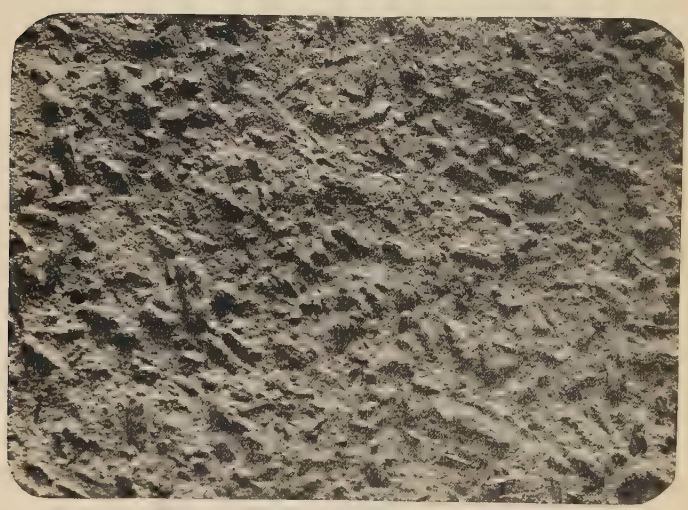
Origin of Porphyritic Texture. In the case of many effusive rocks or lavas it is easy to understand why they have a porphyritic texture. The lavas of many volcanoes, as they issue to the outer air, are full of growing crystals, often of considerable size, suspended in the molten fluid. The latter, however, subjected to new conditions, is forced to cool rapidly and assumes a fine-grained, or minutely crystalline, or even a glassy, solid condition with these larger crystals embedded in it, and thus the completed rock has a porphyritic fabric. The same process may serve to explain this texture in some of the smaller intrusives, such as dikes and sheets, but it cannot serve as a general explanation for all cases, because in some dikes, laccoliths, etc., there is good evidence that the phenocrysts have not been brought thither but have formed, like the rest of the rock, in the place where we now find them. It also fails to explain the porphyritic border of many granites and the large phenocrysts found in other granites; nor does it explain the origin of the phenocrysts themselves, nor make plain why a few large crystals have formed while the rest of the magma fails to crystallize. Evidently some more general explanation is needed.

It has been previously shown that molten magmas must be considered as strong or saturated solutions of some compounds in others. As the mass cools down it may become supersaturated. Now, it has been shown that some saturated solutions cannot crystallize spontaneously but require to be inoculated with a minute fragment of the substance in solution; this is called the *metastable* state. Other saturated or supersaturated

PLATE 7.



A. With Phenocrysts of Feldspar.



B. With Phenocrysts of Augite.

PORPHYRITIC TEXTURE.

solutions either crystallize spontaneously or can be induced to do so by shaking or stirring with a foreign substance.

Miers has shown that the same solution may pass from one to the other of these states in accordance with changes of temperature, and suggests that a magma in the metastable condition, in which a relatively few crystals induced by inoculation from the surrounding rocks are growing as phenocrysts, may by cooling pass into the labile condition, whereupon spontaneous crystallization of the remaining liquid will ensue and form the groundmass. Or the magma may start in the labile condition, and be reduced by the formation of a crop of phenocrysts to the metastable state, in which condition it may be erupted as a lava, or, remaining and cooling down, it may pass into a new labile state, thereupon crystallize and form the groundmass. The recognition of these states in cooling saturated solutions (and we must regard the molten magmas as such) seems quite sufficient to explain the different variations of porphyritic texture which occur.

Some Structures of Igneous Rocks

The word *texture* is reserved for those features of the rocks that are occasioned by the size, shape, color, etc., of the component crystal grains. Certain larger features exhibited by the rocks may be classed under the term of *structure* and will now be described.*

Vesicular Structures. When a molten magma rises to the surface, and especially if it issues as a lava flow, the pressure upon it is relieved and the water and other vapors it may contain are given off. This has a tendency, if it is still soft and stiffening, to puff it up into spongy vesicular forms, as illustrated in Plate 8. Very siliceous lavas may, indeed, be entirely changed into a light glass froth called *pumice*. Such forms are

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* An example of the difference between the two usages would be this. A certain lava from flowage might appear in layers; the layers are of rock composed of exceedingly fine particles. We would say then that the lava had a banded structure and a very fine compact texture.

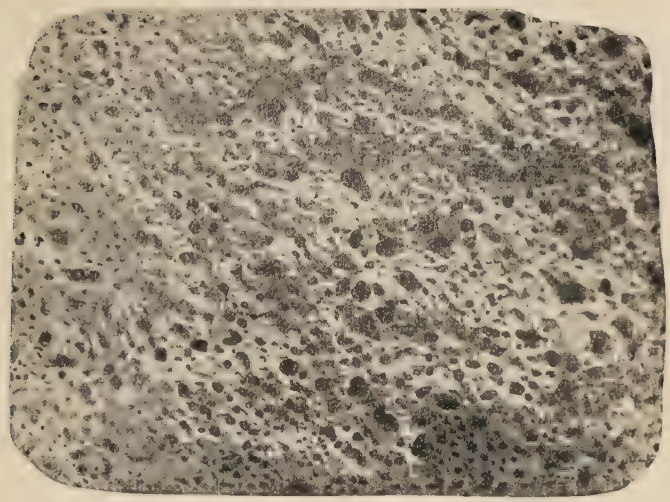
especially produced in the lava in the throat of a volcano, where the issue of gases is rapid, or in the top portion of a flow. Except in a rare and very limited way in dikes and sills, they never occur in intrusive rocks, and the presence of well-marked vesicular structure may be taken as pretty sure evidence that the rock exhibiting it was originally a surface lava. In the throat of a volcano such spongy forms of lava may, by explosions of steam, be driven in fragments into the air to fall as dust, ashes, lapilli, etc., making volcanic tuffs and breccias as described elsewhere.

Amygdaloidal Structure. Amygdaloid. When a lava has been rendered spongy (vesicular, as described above), it may be permeated by heated waters carrying material in solution which may be deposited as minerals in the cavities. This happens especially in basaltic lavas, and the dark rock then appears filled with round or ovoid whitish bodies which, from the frequent resemblance of their shapes to almonds, are termed *amygdules*, from the Greek word for the almond. The structure is called the *amygdaloidal,* and a rock exhibiting it is often termed an amygdaloid. It is shown in Plate 8. While the smaller cavities are usually filled solid, the larger ones are often hollow, the minerals projecting in crystals from the walls as in geodes, and from such amygdaloidal cavities some of the most beautiful crystallizations are obtained. The minerals most frequently occurring are quartz, which is sometimes of the amethyst variety, calcite, and particularly zeolites. The basaltic lavas are an especial home of the zeolites, some of the more common kinds being analcite, stilbite, natrolite, heulandite, and chabazite. The basalts of India, Iceland, Scotland, Nova Scotia, and other localities have furnished specimens which are known in all mineral collections.

The amygdaloidal structure is most commonly developed in surface lavas, that is, in effusive rocks, but it is also seen in places in intrusive rocks, such as dikes and sills, especially at their margins.

Miarolitic Structure and Porosity. The volume which a magma occupies in the molten condition is considerably greater

PLATE 8.



A. VESICULAR LAVA.

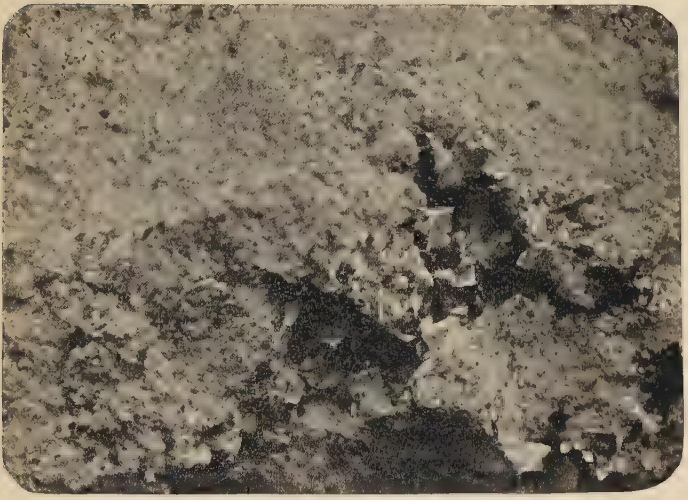
B. AMYGDALOIDAL BASALT.

than that which it has when changed to a solid crystalline rock. It is probably greater in the liquid state than when cooled to a glass, but how much we do not know. This contraction in volume, in passing into the crystalline state, is accompanied by a corresponding rise in specific gravity. Thus an obsidian glass, consisting chiefly of high silica with moderate amounts of alkalies and alumina, has an average specific gravity of about 2.2 to 2.3, but the same material crystallized into a quartz-feldspar rock (granite) has a specific gravity of 2.6 to 2.7. There would be a corresponding reduction in volume.

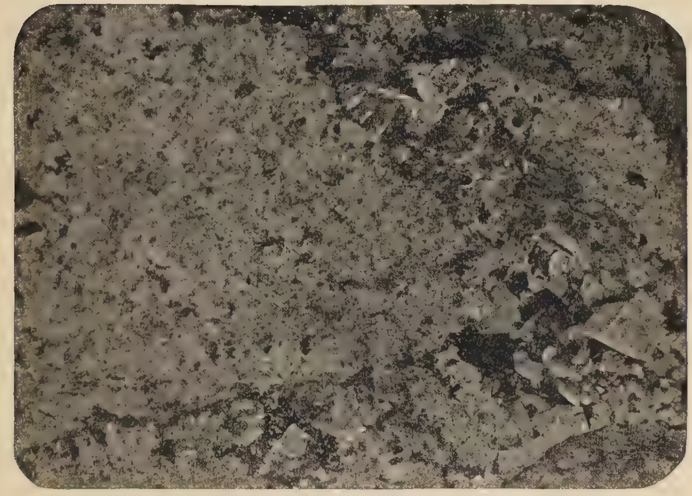
In general, this contraction in volume, during the process of crystallizing, produces minute interspaces or pores between the mineral grains, and cracking and jointing of the mass, a process described in the following section. This production of pores accounts for the capacity of the rocks to absorb moisture. It appears to be greatest in the coarse-textured rocks, much less in the finer-grained ones; greater in granites, less in diorites and other ferromagnesian rocks. In porous vesicular lavas the amount of pore space may be very great, but in ordinary crystalline igneous rocks it is small, usually less than one per cent of the rock volume.

In some places, however, there may be distinct cavities produced. These are commonly very small, sometimes an inch or so in diameter and in rare instances as much as several feet. It often happens that the crystal components of the rock on the boundary walls of the cavity are much larger in size than the average grain, and project into it, bounded by distinct faces and of good crystal form. One notices also, especially in granites, that the quartz and feldspar crystals are often accompanied by those of muscovite, topaz, tourmaline, and others which are foreign to the general mass of the rock but are common in pegmatite veins. These are also well crystallized. The presence of the water vapor, fluorine, boron, etc., necessary for their production, as well as the larger size and distinct form of the crystals, shows that such mineralizers, excluded elsewhere from the magma during the process of crystallization,

PLATE 9.



A. MIAROLITIC CAVITY.



B. MIAROLITIC MINERAL AGGREGATES TRANSITIONAL INTO PEGMATITE.

collected in these cavities, possibly helped to enlarge them, and promoted the formation of the unusual minerals and the good crystal forms which they and the ordinary rock minerals exhibit. Such hollow spaces are called *miarolitic cavities*, and a rock that contains them is said to have *miarolitic structure*, from a local Italian name (*miarolo*) for the Baveno granite which shows it. Such drusy cavities are distinguished from geodes and others, in which the minerals have been deposited from solutions, by the fact that they have no distinct wall separating the minerals from the containing rock. They often furnish fine mineral specimens. An example of a miarolitic cavity is seen in Plate 9.

Jointing of Igneous Rocks. After a body of magma has cooled and crystallized into rock, the most important visible effect of the contraction that has taken place is the presence of joints. These are the cracks or fissures which, running in various directions, divide the mass into blocks, fitted together like masonry and usually according to more or less definite systems. Sometimes this jointing shows itself in the formation of rudely cubic or rhomboidal blocks, as shown in granites and other abyssal rocks, sometimes in a platy parting which may be quite thin and cause the rock mass at first glance to resemble sedimentary beds, and sometimes in concentric or spheroidal forms which develop rounded or ovoid bodies like melons as the weathering and rock decay progresses. Platy and spheroidal partings, and jointing on a small scale by which the rock body is divided into little blocks, are most common in small intrusions — in dikes, sheets, etc. — and in surface lavas. Such jointing is a matter of great geologic importance because it permits the entrance of air and water to act in the weathering and decay of rocks and in the processes of erosion, especially rock-splitting by frost action. As can be readily inferred, it is also of great practical importance in the work of rock excavation, in mining operations and in quarrying. (See Plate 10.) Were it not for such joints almost every igneous rock mass would furnish suitable material for quarrying, whereas on the contrary it is difficult to find a granite jointed on so large a scale

PLATE 10.

A. High Isle Quarry, Maine.

B. Allen Quarry, Mount Desert, Maine.

JOINTING IN GRANITE AND ITS USE IN QUARRYING.

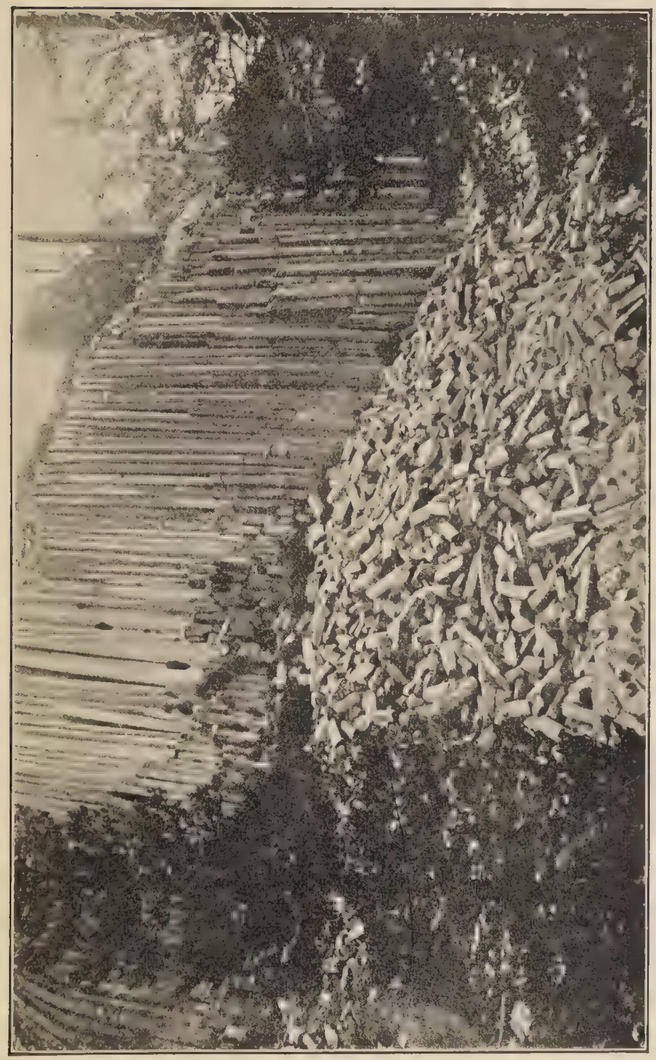
(U. S. Geological Survey.)

that it will furnish single blocks of great size, for example, like those from which the celebrated Egyptian obelisks were made.

Columnar Structure. The jointing of a cooling mass of igneous rock manifests itself in the most remarkable way in the production of columnar structure. This is found both in intrusive and extrusive occurrences and in all kinds of igneous rocks, but is usually best displayed in basalts. The whole mass is made up of columns, regularly fitted together, from a few inches to several feet in diameter and from one foot to two hundred feet or even more in length. An example is shown in Plate 11. The celebrated Giant's Causeway on the north coast of Ireland is one of the best known examples of this. In the most perfect cases, as in the one just mentioned, the cross sections of the columns are regular hexagons and the columns are divided lengthwise at regular intervals by cross joints whose upper surfaces are shallow cup-shaped. The columns are always perpendicular to the greatest extension or main cooling surface of the igneous mass, hence in a lava flow or intrusive sheet they are vertical — assuming the flow or sheet to be horizontal — while in a dike they tend to be horizontal. Such a dike when exposed by erosion tends to resemble a stretch of cord-wood regularly piled.

The cause of this structure seems to be as follows. When a homogeneous mass is cooling slowly and regularly, centers of cracking tend to occur on the cooling surfaces at equally spaced intervals. From each central interspace three cracks radiate outward at angles of 120 degrees from each other. These, intersecting, produce regular hexagons, and the cracks, penetrating downward, make columns. This regular arrangement produces the greatest amount of contraction with the least amount of cracking, provided the centers are equally spaced. But as the contractional centers are not always equally spaced, three, four, five, seven, and eight-sided columns occur. The columns again, contracting lengthwise, break into sections as they form. The same principle is also seen in drying mud-flats which crack into polygonal shapes, and in the prisms of drying

PLATE 11.



COLUMNAR STRUCTURE IN LAVA, SAN JOAQUIN RIVER, CALIFORNIA.

(U. S. Geological Survey.)

and contracting starch. Such columns, however regular their appearance, are not crystals but pieces of rock and should not be confused with the hexagonal prisms produced by the crystallization of certain minerals, such as quartz, beryl, etc., which are formed by an entirely different process.

Inclusions in Igneous Rocks

Not infrequently there may be noticed in igneous rocks masses which differ in mineral composition, color, and texture from the rock which includes them. They may vary in size from a fraction of an inch to several yards across. Study of them shows that sometimes they present all the characters of distinct kinds of rock and by these, and by their angular shapes, they show clearly that they are either fragments of pre-existent rocks which the magma on its way upward has torn loose from the walls of its conduit and brought along, or else they are blocks from the roof or sides of the chamber in which the magma came to rest, which were loosened and sank into it. They may be composed of other kinds of igneous rocks or of sedimentary ones, such as shales, limestones, etc. Inclusions of igneous rock are not usually much changed, but the fragments of stratified rocks generally exhibit the results of intense metamorphic action, such as described elsewhere, and are much altered. In large intrusive masses inclusions of this character are most likely to occur near the border. An inclusion in granite is shown in Fig. 1, Plate 12.

In other instances the inclusions are composed of certain minerals, especially the ferromagnesian ones, which occur in the rocks and which by some process have been aggregated into lumps, such as the masses of olivine crystals often found in basalts. It is clear that such aggregation or growth of these minerals must have taken place while the remainder of the rock was still in a liquid condition. They have been termed *segregations*.

In still another kind the inclusions are indefinite in form and in boundary; they are likely to be drawn out, lenticular, and streaky in character, and they may consist of the same minerals as the main mass of the rock but in quite different proportions, or they may contain different minerals. Thus one sees streaks in granite which may be much richer in hornblende or biotite than the enclosing rock. Some have held that these streaks are due to inclusions of other rocks which have been melted up and then recrystallized, and in some cases they may have had this origin, but for the most part they are regarded by petrographers as caused by streaks and spots in the original magma of a different chemical composition from the main portion. The cause of such non-homogeneousness in the magma is ascribed to differentiation, as discussed elsewhere in this volume. Such streaky portions are called by the Germans *schlieren* and in default of anything better this word is often used for them in English.

Sometimes lavas show a streaky or even a well-banded structure, portions differing from one another in composition or in texture having been drawn out in the flowage. This is known as the *eutaxitic* structure.

Origin of Igneous Rocks — Differentiation

The fact that lavas differing decidedly from each other in mineral and consequently in chemical composition have been erupted by the same volcano at different periods early attracted the attention of geologists and led to much speculation as to its cause. Thus felsites and basalts have both been frequently noticed as the products of eruption from a single vent. One explanation, which used to be advanced, was that within the Earth there were two layers of magma, an upper one rich in silica, alumina, and alkalies, the other and lower, poor in silica but rich in iron and magnesia; according as the eruption came from one or the other of these layers, felsites or basalts were produced, while their mixtures gave rise to intermediate products. It was soon seen, however, both on chemical and geological grounds, that this view was insufficient to explain the origin of all igneous rocks.

As the study of rocks progressed, other facts of a similar nature came to light. Thus in the single rock mass composing the core or neck of an old volcano,* where the magma cooled under conditions favorable for the production of the even-granular or granitic texture, it is not infrequent to find that it is composed of two or more distinct kinds of rock. The boundary between these will sometimes show that one was erupted after the other had solidified in its place, since fragments of the latter are enclosed in the former. This is, of course, merely carrying deeper down into the volcanic conduit the same facts shown by the surface lavas previously mentioned. Other phenomena, however, are of a different nature and of such geological importance that they demand separate consideration.

Border Zones. In recent years the study of deep-seated intrusive masses, such as stocks of granite, syenite, etc., which have become exposed by long-continued erosion, has shown that not uncommonly such masses have an outer border or mantle of rock which differs in mineral composition from the mass which it enfolds. The thickness of such a border zone is very variable, even in the same mass, and in places it may be lacking; it may be several thousand feet thick or only a few hundred or even less. While in general it bears some proportion to the size of the whole mass, there is no rule about this which can be stated.

As a rule this zone, or *border facies*, as it is sometimes called, is produced by an enrichment of the rock in the ferromagnesian minerals, such as pyroxene, hornblende, biotite, and magnetite. Generally the enriching minerals are the same as those more sparsely distributed in the main rock body but very often different ones are observed among them. From this it is clear that chemically the border zone is richer in iron and magnesia, and to some extent in lime, than the main mass, with a corresponding diminishing of silica, alumina, and alkalies. Since they contain less of silica, the acid oxide, they are commonly called *basic* zones. Not all border zones, however, are basic ones;

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* See volcanic necks, page 134.

a number of instances are known in which the margin of the intrusion is poorer in lime, iron, and magnesia and consequently in ferromagnesian minerals than the interior rock body, and therefore contains more silica, alumina, and alkalies, a condition which expresses itself mineralogically in a greater abundance of feldspar or of feldspar and quartz. They are then called *acidic* border zones. Thus on the one hand intrusions of syenite have been found which pass into pyroxenite at the border, while on the other hand syenite intrusions are known which become granite towards their margin. It must not be imagined that there is any definite contact between the rock of the main mass and its border zone. The one kind passes gradually into the other without change in texture, and all the facts indicate that this arrangement was not produced by successive intrusions of different magmas but by some process in a single body of magma after it had entered into its chamber.

Zoned Laccoliths. The zonal arrangement just mentioned is still more strikingly shown in certain laccoliths which have been found in Montana and elsewhere. Where these have been laid bare and dissected by erosion, the study of them shows that they consist of a body of rock of one kind, generally consisting mostly of pyroxene, enclosing a core of rock of a totally different kind, usually a syenite, which is of course chiefly feldspar. A cross section through such a laccolith is shown in the accompanying diagram, Fig. 70.

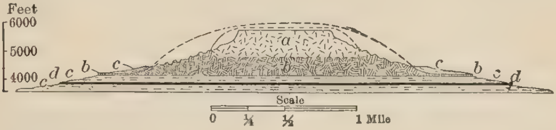

Fig. 70. Diagram of a Zoned Laccolith: *a*, feldspar rock; *b*, pyroxene rock; *c*, shales and sandstone; *d*, underlying sheet of intrusive basalt. Figures in feet are heights above sea-level.

That the pyroxenic rock once had the extension shown by the restoration in the figure is known from other examples in the neighborhood where the erosion has not been so great, and it is still found above, enwrapping the interior syenite.

Associated Complementary Dikes. Another phenomenon, of the same category as those just described, is seen in the dikes so commonly associated with such large intrusive bodies as stocks of granite, syenite, diorite, etc., where these have become exposed by dissective erosion. The dikes are subsequent in origin to the main mass which they accompany, and are found cutting it and also the surrounding rocks. In the latter, these minor intrusions may appear, not only in the form of dikes, but also in intrusive sheets, laccoliths, etc. These rocks are divisible into two classes; in the first they are very poor or entirely wanting in ferromagnesian minerals (salic rocks) and have been called *aplitic* dikes, since the dikes of aplite that are generally associated with granites are the most common and best known representatives of this class. They have also been called *leucocratic* dikes (from the Greek, white predominating) in allusion to their general light color, due to the fact that they are composed mostly of feldspars or of feldspars and quartz. They are generally fine-grained rocks: some are of a sugar granular texture, some are aphanitic and to be classed as felsites. Some are porphyritic. They usually occur in narrow dikes, a few feet wide and sometimes only an inch or even less in breadth.

In the second class the rocks are heavy, dark or even black, of basaltic aspect and composed chiefly of ferromagnesian minerals, magnetite, pyroxene, hornblende, biotite, and olivine, in variable amounts and with very subordinate feldspar. They are very commonly porphyritic, with good-sized phenocrysts of the minerals mentioned in an aphanitic dark groundmass. However, they are often non-porphyritic. Such rocks have been called *lamprophyres* (from the Greek, meaning glistening porphyry, in allusion to the biotite), and are termed *melanocratic* rocks, or rocks in which the dark minerals predominate (from the Greek μελανός, black, and κρατεῖν, to rule). In our field classification they would be named biotite melaphyre (or mica trap), hornblende melaphyre, etc., according to the prevailing phenocrysts. They also usually occur in narrow dikes and are more likely to cut the surrounding rocks than the main intrusive body they accompany, thus reversing the custom of the aplites.

These two kinds of rocks, the aplitic, light-colored feldspathic, and the lamprophyric, dark-colored, with ferromagnesian minerals, are termed *complementary* because taken together they represent the composition of the main masses they accompany. If we could mix them in amounts proportional to the bulk of their occurrence we should obtain a rock whose chemical (and largely mineral) composition would be that of these larger masses upon which they appear to depend as satellite bodies. For some occurrences this has been actually tested and proved. When all the facts concerning the mode of occurrence of these satellitic dikes are taken into account they appear to have been formed by secondary, later intrusions of the same magma that produced the larger stocks, which in some way has divided into two unlike sub-magmas. If they should break through to the surface they would give rise to dissimilar lava flows as, for example, to felsites and basalts. They thus explain in part the phenomena noticed in many volcanoes.

It is to be understood, of course, that not all dikes belong in this category of complementary rocks. On the contrary we very often find that the same magma that produces stocks, necks, etc., occurs also as dikes. These dikes then have the same minerals and composition as the larger masses, or if in disconnected bodies they usually contain both ferromagnesian and feldspathic minerals in the same amount as in the parent mass. Only, as explained on page 152, they are likely to differ in texture from the stocks and generally are porphyries. Dikes and other bodies of this kind have been called *aschistic,* which means undivided, while the complementary aplites and lamprophyres have been termed *diaschistic*, which means divided, in allusion to their origin by the division or splitting of the original magma into two fractions.

Differentiation. The varied lavas of volcanoes, the marginal zones of stocks and necks, the zoned laccoliths, and the associated complementary rocks, which have been described in foregoing sections, as well as other similar features, present to us a body of geological facts that can be satisfactorily explained only by the assumption that in some way the magmas that form igneous rocks have the capacity of separating into sub-magmas which are unlike the original, but which, if mixed in proper proportions to a homogeneous whole, would again reproduce it. In the process of division there seem to be in general two opposite poles toward which the sub-magmas tend; toward one there is a concentration of the iron, magnesia, and to a large extent the lime; toward the other, a concentration of the alkalies, alumina, and to a great extent the silica. The one gives us ferromagnesian rocks such as gabbro, the other feldspathic rocks such as granite. While this is so in general, we find that the details of the process in nature are infinitely varied; thus in some places one may observe a further subdivision among the alkalies, an enrichment of potash towards one pole as compared with soda, or vice versa. If this process of differentiation takes place after the magma has come to rest in its chamber and while it is crystallizing, solidifying, and forming rock, the resulting rock body will evidently be unlike in its different parts, and marginal zones, zoned laccoliths, etc., will be produced; or if further movements occur, producing new intrusions or intrusions accompanied by extrusions, then associated complementary dikes, sills, and lava flows may occur.

This division into sub-magmas is termed the *differentiation of igneous magmas* and the reality of it as a process is well established on geological grounds by a large body of facts. To realize that such a process does take place and to understand how and why it takes place, are two entirely different matters, and while everyone who is thoroughly conversant with the facts is obliged to admit the former, a wide diversity of views, owing to insufficient knowledge, prevails in regard to the latter. Some phases of this subject are discussed in the following paragraphs.

Formation of Zones and Ore Bodies. One partial explanation that has been offered for the zoned structures previously mentioned is of importance because it affords at the same time an understanding of the origin of a certain class of ore bodies which in some places are of considerable extent and value. On page 147 it is shown that there is a general order of crystallization of rock minerals, beginning with the iron ores, then passing to the ferromagnesian silicates, and finishing with the feldspars and quartz. In an enclosed body of magma, crystallization would generally begin when the temperature had fallen to the proper degree. This would naturally first occur at the outer walls where the effect of cooling is first felt. Against these the iron ores and ferromagnesian minerals, the earliest to crystallize, would form and, if the process were extremely gradual, slow convection currents in the magma would bring fresh supplies of material to crystallize there until large amounts of these minerals had formed. This might go on until the temperature had fallen to a point where the main body of magma was compelled to solidify and the rock mass as a whole was produced. The outer margin would be much enriched in the earlier-formed minerals, giving a zoned arrangement to the whole mass.

Origin of Salic Border Zones. The explanation given above would show how marginal zones richer in ferromagnesian minerals might arise; but it has been observed that masses of granitic and syenitic rock are sometimes poorer in these minerals, or deprived of them, at the margin of the mass while the main part contains them in considerable amounts, thus making salic zones. An explanation which has been offered for this is as follows: If a solution of a salt in a liquid (such as sea-water) be cooled down until it is forced to crystallize (freeze) it is found that the substance in greatest excess, salt or liquid, will solidify first until a certain definite proportion of dissolved salt and liquid, called the *eutectic* mixture, is obtained, whereupon the remaining salt and the remaining liquid will both crystallize simultaneously and the whole mass become solid.

The proportion of salt to fluid forming the eutectic varies with the kind of salt and of solvent. Thus when sea-water freezes the ice first formed contains no salt, the latter forming in the remaining water a brine of increasing strength until the eutectic point is reached, when both solidify together. In the case of granite and syenite the quartz and feldspars are present in great excess and may be considered the solvent for the others. It is possible that under proper conditions these might solidify at the outer margin, the other minerals concentrating in the remaining portion and tending to make a eutectic mixture. Thus when the whole solidifies the inner part will contain ferromagnesian minerals, and the outer part will be poor or wanting in them. In many diorites and gabbros, in which the ferromagnesian minerals are in great excess, they would be the solvent, and we should expect border zones of ferromagnesian minerals. It is evident that this explanation, and the one previously given, which depends on the order of crystallization, are, in highly feldspathic rocks, opposed to each other: the first tends to make ferromagnesian zones around granite and syenite, the latter salic ones. In the diorites and gabbros both tend to produce margins richer in ferromagnesian minerals.

Zones by Absorption. It has also been suggested that such zones are produced by the magma melting its containing walls and thus, by absorbing foreign material, becoming in composition, at its border, unlike the main mass. Being thus unlike, it would naturally have a different mineral composition on solidification. It is possible that this may have happened in some places; but it cannot serve as a general explanation, because we frequently find the border to be of an entirely different mineral (and chemical) composition from that which we might expect it to be if the rocks with which it came in contact had been melted and absorbed.

General Explanation. It is obvious that the hypotheses discussed above, while they may serve to explain border zones and marginal ore deposits, do not give a general explanation for the differentiation of igneous rocks. The occurrence of complementary dikes, of the eruption of different lavas from the same volcano, and the mixtures of different types, which are not marginal, in the same stock, as well as other facts, show clearly that differentiation is not as a rule a division by a process of solidification, but one that occurs in a magma in such a manner as to produce separate bodies of differing *liquids* which may be independently ejected or intruded. It must occur before there is any solidification. While we see that this is so, both from geological and chemical facts, no general explanation, which is in all respects satisfactory, has been offered for this process. Different hypotheses, which it would be beyond the limits of this work to state and discuss, have been suggested by various authorities, but our knowledge of the physical chemistry of molten magmas is as yet too limited to enable us to estimate the proper value and applicability of these hypotheses. —Thu.

Petrographic Provinces. Consanguinity. It has been noticed in the study of rocks that those rocks belonging to certain regions have particular features which to a greater or less degree are distinctive of all the members of the group that occur there. This community of characters is shown by the presence of particular varieties of minerals, sometimes by peculiar textures, sometimes by peculiarities of chemical composition, and usually by a combination of these things. These characteristics may be shown in varying degrees by all the different rocks of the region: thus, for example, by syenites which are chiefly composed of feldspar and by dolerites in which ferromagnesian minerals prevail; in intrusive stocks of granular rocks with their associated complementary dikes and sheets, and in lava flows of felsites and basalts. These common characters are sometimes strongly marked and at other times to be seen only by the experienced observer. The fact that such distinguishing features occur in the different types of a certain region and serve to indicate their relationship to one another and to show a common origin by differentiation is termed the *consanguinity* of igneous rocks, and that region over which the rocks thus show genetic relations is called a *petrographic province*, or *comagmatic* region. Thus the comagmatic region of south Norway is characterized by the extremely high percentage of soda in the magmas, which gives rise to certain minerals and peculiar rock textures; those of Italy and central Montana by very high potash, which shows itself in the formation of the mineral leucite, common in such regions but rare or unknown elsewhere; that of the western Mediterranean islands and eastern Spain by an abnormally high amount of titanic oxide in its rocks.

Such evidences of consanguinity in rock groups and the proofs which they furnish of comagmatic regions cannot usually be observed in field work and in the megascopic study and determination of rocks. They generally demand careful and complete investigation of thin sections under the microscope, aided by chemical analyses in the laboratory, together with a broad acquaintance with the literature of this subject, in order to be perceived and appreciated. The matter, however, is one of great interest, and although one may not be either a chemist or petrographer, he may yet appreciate the significance of its bearing on the solution of problems of the greatest importance in geology. It is evident that before we can safely theorize as to the origin and history of the Earth we must first know the nature of its component parts and the laws governing their distribution.

Post-intrusive Processes

When a body of molten magma has come to rest in the chamber it is destined thenceforth to occupy as a solidified rock mass, cooling and eventually crystallization begin. From this point on, so far as the magma is concerned, those factors are at work which have been described elsewhere, and which in time will produce the completed rock. During this period of crystallization the volatile substances dissolved in the magma and previously contained under pressure, such as fluorine, boric acid, carbon dioxide, and especially and chiefly water, which have already been described as *mineralizers*, are gradually excluded, except in so far as they may take part in the chemical composition of some of the minerals.

This period in the history of the formation of a rock body, when it is solidifying and giving off, as it crystallizes, heat and vapors, is called the *pneumatolytic* (Greek, gas, and to loosen), and these agents generate important results. At the surface they give rise to hot springs, fumaroles, solfataras, and similar secondary igneous phenomena; in the depths they produce in the rocks surrounding the igneous mass a variety of features known under the term of *contact metamorphism;* and in the already solidified parts of the igneous mass they bring about the formation of *pegmatite dikes*, of *greisen* (described under Granite), and in some places of *ore deposits*. These things are treated in the following sections.

Pegmatite Dikes or Veins. It has been previously stated that when deeply formed stocks or masses of granite, syenite, diorite, etc., have been laid bare by erosion they are very frequently found to be cut by complementary dikes of aplite and lamprophyre. In addition it is also frequently observed that they are penetrated by dikes which display certain definite characters, the most marked of which is the very large and sometimes enormous size of the individual minerals composing them. Such dikes have been termed *pegmatite* dikes, from the name given by Hauy to the remarkable " graphic " intergrowths of quartz and feldspar found in them when they occur associated with granites. Dikes of this character not only cut the stocks and batholiths to whose intrusion they owe their origin, but are also found penetrating, as offshoots, the rock masses enveloping them. There are a number of features which particularly characterize them, as follows:

a. They consist in large part of the ordinary minerals that compose the granite or similar rock with which they are genetically associated, but these minerals, instead of having their regular order of successive crystallization, show by their interpenetration that they have crystallized more nearly, if not entirely, simultaneously.* The size of the individual crystals is a character that has been mentioned. Feldspar and quartz may occur in crystals a foot or even several feet long, apatite in dimensions like the handle of a broom, mica in crystals yielding plates a foot or more in diameter, and other minerals in similar proportions. It is not to be understood that these sizes represent the average; they are the extremes which are, however, not infrequently attained.

b. Another peculiar feature is that in many pegmatites there is an obvious tendency for the minerals to grow outward from the walls of the dike on either side and project inward toward the center. This may become very marked and there may even be an empty space at the center into which the minerals project, showing crystal faces as in miarolitic cavities (page 160) or in the vugs of mineral veins. The whole effect is to produce in a rough way a zoned, banded, or ribbon structure, like that often so perfectly seen in mineral veins.

c. Another character is the extreme variability in the relative proportions of the component minerals from place to place, a variability not seen in the main igneous rock mass with which the pegmatite is associated. Thus in granite pegmatite dikes when traced along their outcrops, great variations in the relative amount of quartz and feldspar may often be observed; traced outward from the parent mass into the enclosing rocks, they may even pass into pure quartz veins. In other cases they may turn into fine-grained granite (aplite) or felsite, and this change in the character of the dike may occur quite suddenly.

d. They are very likely to contain accessory minerals which are either not found at all in the main rock mass or which microscopic examination shows are sparingly distributed in very minute crystals. These minerals may be divided into two classes. In the one their chemical composition shows that they consist of the ordinary oxides which compose the magmas, alumina, lime, iron, soda, etc., plus the volatile elements which

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* See in connection with this the description of graphic granite in the granite pegmatite veins, p. 217.

form the mineralizing vapors. Common ones are tourmaline, which shows the presence of boric acid; topaz and fluorite, which demonstrate that fluorine was present; and many, of which muscovite mica is perhaps the most prominent, which prove the important rôle played by water vapor. The minerals of the other class are characterized by their containing in larger or smaller amounts the rare elements, such as lithium, cæsium, beryllium, molybdenum, cerium, lanthanum, columbium, etc., elements that are detectible with difficulty as minute traces or not at all in the parent rock mass. In combination with silica, titanic oxide, phosphoric acid, zirconia, carbonic acid, fluorine, etc., they give rise to a whole host of minerals too numerous to mention, but of which beryl and spodumene may be cited as examples. No sharp distinction can be drawn between these two classes; many minerals might be placed in either, but definite types of both, like those mentioned, can readily be found.

These accessory minerals often occur in crystals of great size, and in some dikes are locally aggregated in very large amounts. It is due to this great variety of minerals and the frequent large size and perfection of the crystals that the pegmatite dikes are mineralogically of great interest and are, therefore, a favorite hunting ground of mineral collectors. It is to be noted also that each variety of magma (or rock) is characterized by special mineral combinations in its pegmatite dikes, and this applies not only to the ordinary minerals that compose the pegmatites and distinguish them from one another but also to the accessory minerals as well.

Thus the minerals in the pegmatites that are associated with ordinary granites are quite different from the minerals occurring in the pegmatites associated with the nephelite syenites, as these in turn differ from those of the gabbros.

Origin of the Pegmatites. The simultaneous method of crystallization, the arrangements along the walls of the dike, the variability in the proportions of the component minerals, and their frequent huge size all show that the conditions prevailing during the formation of the pegmatites were different from those which attended the solidification of the main rock masses. The presence of hydroxyl, fluorine, boron, etc., also shows that mineralizing agents were abundantly present. Bearing these facts and those of the geologic mode of occurrence in mind, we can present to ourselves a view of the origin of the pegmatites which would be somewhat as follows:

When a body of igneous magma, such as will form a stock or batholith, comes to rest in place it will commence to cool. This cooling will naturally take place first in the upper and outer portions, and here will begin the solidifying of the mass by crystallization. As it becomes solid it breaks up into jointed masses by contraction. The weight of these masses, aided by the rock pressures from above upon the still liquid material below, tends to force the magma upward into the fissures in the solidified part and into those of the surrounding rocks and thus to produce dikes. If differentiation is taking place and there is a concentration of the iron, magnesia, and lime toward the outer border, as explained in previous sections, these dikes will be complementary and we shall find aplites (and felsites) more commonly in the central mass, and the corresponding lamprophyres more commonly in the outer portion and in the surrounding rocks.

But as the process of crystallization goes on, the volatile substances in the magma, and especially water in great quantities, beyond what is retained by such minerals as use these substances in their chemical composition, will become concentrated in the still unconsolidated portion of the magma, and as the gases accumulate more and more their pressure must increase enormously. Consequently they will tend to force their way upward along the fissures in the solidified parts above and at the sides. These cracks will therefore become channel ways for the still unconsolidated magma, whether differentiated or not, and they will also afford avenues of escape for the vapors that collect in them and in the cracks in the surrounding rock mantle, under pressures that must generally be enormous. It is evident from this that the ascending magmas in the fissures will at various places become supercharged with these vapors far in excess of the content in the normal rock. Now, both on experimental grounds and from observations in nature, it may be regarded as almost certain that no sharp line can be drawn between igneous fusions of silicates (molten silicate magmas) containing water under pressure and hot water solutions. It appears that under pressure water will mix in all proportions with magma, so that at one end are molten fusions, at the other hot water solutions.*

At 375° C. water reaches its critical point; that is, heated to this degree, or above, its vapor cannot be turned back into liquid by mere pressure, however great this may be. At this temperature its expansive force is almost 3000 pounds to the square inch, which would require a vertical height of about 2500 feet of granite rock to contain it. Above this temperature sufficient pressures cause it to contract rapidly and it may even occupy less volume than it would occupy in the liquid state. The temperatures obtaining in molten rock magma are far above the critical temperature of water and it must therefore be in the gaseous condition, though under the enormous pressures obtaining beneath thousands of feet or even several miles of overlying rock, it may well be much denser than water at the surface. Although it has not yet been shown, so far as the writer knows, that water in this state holds substances in solution just as though it were a liquid, we can well imagine that at high temperatures, aided by the fluorine and other active substances so commonly with it, its solvent action must be enormously increased, especially its ability to dissolve silica.

It is easy to see that under such conditions the minerals would crystallize quite differently from those in the normal rock; in some places the silicate portion of the magma would be in excess and the results would more nearly approximate those obtaining

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* A good illustration of this is seen in a solution of thallium silver nitrate, which boils down, losing water, until there remains a clear molten fluid of the double salt which is anhydrous.

in the main body of magma; with diminished water content the dike might pass into an ordinary aplite or felsite phase; with increased amounts, in another place, it might pass from the state of a magma into an aqueous solution and here would be favorable conditions for the development of crystals of gigantic size, for growth outward from the walls, and for the segregation of the rarer elements. Finally, passing onward, the water content might become more pronounced, only silica would be carried, and the dike might turn into a quartz vein. Thus, as the degree of differentiation of the magma and the content of water in the magma vary, we can see how dikes of ordinary rock, of variable pegmatites, and quartz veins may be formed, which in places show very clearly their genetic relationships.

Contact Metamorphism. This term is applied to the changes which are caused by a body of magma coming in contact with other rocks already formed. The word metamorphism, from the Greek, means a change of form or body and is applied to those results, induced by a variety of factors, by which rocks are recrystallized with the formation of new minerals and textures. General or *regional* metamorphism, by which rocks are changed over wide areas through various geological agencies, is considered in a later chapter; here only the results caused by igneous magmas are treated. In several ways the results of the two are alike and they often merge into one another, but in contact metamorphism the extent of the masses involved is, in general, much less than in regional metamorphism.

The effects of the contact of a body of magma with other rocks are seen in two ways: in one, termed the *endomorphic* effect, a change from its general normal character is commonly observed in the igneous rock itself; in the other, called the *exomorphic* effect, there are changes in the rocks with which this igneous rock has come in contact. We shall consider the former one first.

Endomorphic Effects. It has been stated in a previous section that a change in the mineralogical composition of an intrusive rock body is not infrequently observed along the contact, producing a border zone or facies. This is due to a change in the chemical composition of the magma, caused by differentiation, and has been fully discussed. But at times also, even when this process has not occurred, more or less of a change in the minerals of the igneous rock may be seen directly at the contact or as one approaches it. In this case it is due to the presence of mineralizing vapors which, as previously described, tend to be expelled as the mass cools and crystallizes and to escape to the margin and into surrounding rocks. Through their influence are formed minerals which do not generally occur in the main part of the mass and which have been described as characteristic of the pegmatite dikes. In granites the most characteristic is perhaps tourmaline, the presence of which is indicative of boron, hydroxyl, and fluorine. It tends to take the place of the biotite in the main rock and its occurrence as a regular component of the granite should always lead to a suspicion of approach to the contact, though it is also found in the neighborhood of fissures which have served as the conduit for pneumatolytic exhalations.

A variety of the granite of the Black Hills from Harney Peak illustrates this feature; in addition to the usual quartz and feldspar, the rock contains black tourmaline, abundant and well-crystallized muscovite, green beryl, and red garnets: such minerals recall the associations seen in pegmatites.

It may even happen that the accumulation of mineralizing vapors is so great at the outer margin before crystallization begins that the conditions are favorable there for the formation of a true pegmatite zone. The writer has observed a granite stock in the White Mountains enwrapped by a mantle of pegmatite; the large plates of muscovite are set perpendicular to the contact and the mixture is much enriched in quartz. Similar examples are known from other localities, and in Pelham, Mass., a pegmatite mantle partly enfolds a mass of peridotite in the gneiss. Phenomena of the character described above are most noticeable about the larger intrusions, such as batholiths, stocks, etc.; in dikes, sills, and minor intrusions they are not so conspicuous or are entirely wanting.

A much more common endomorphic contact effect is a change in *texture*. This is independent of any change in mineral composition, in fact, is chiefly observed where the mineral composition remains constant. The most usual feature of this kind is a change in the average size of grain in the rock, which grows smaller as the contact is approached. The rock indeed may become exceedingly fine-grained at the contact; thus for instance a granite with an average grain of the size of coarse shot may turn into a compact, homogeneous appearing felsite. This fine-grained border facies is of course due to a more rapid crystallization set up at a large number of centers, produced by the chilling effect of the contact wall. Instances are even known where the cooling, caused by the cold rocks with which the magma came in contact, was so rapid that solidification took place at the margin before crystallization could begin, with the production of a thin selvage sheet of glass. Such instances are most likely to occur in narrow dikes, in which the cooling effect of the contiguous rocks is most strongly felt.

Moreover, this finer-grained contact facies may contain larger distinct crystals or phenocrysts and thus be a porphyry while the main mass is of even-granular texture. The phenocrysts may have been formed before the magma came to rest; in the main rock body they may be of the same size as the rest of the later rock grains but at the contact their contrast with the material in which they are embedded produces a porphyry. On the other hand, in many intruded masses of porphyry occurring in dikes and sills the phenocrysts may be entirely absent at the contact margin, and in such rock bodies they have been formed after the period of intrusion, since if they had been brought up in the ascending magma they would be found at the contact as well as in the interior of the mass.

The cases treated above are sufficient to illustrate the chief endomorphic effects of contact metamorphism in igneous rocks.

Exomorphic Effects of Contact Metamorphism in General. The effect of the heat and vapors given off by an intruded mass of magma upon the surrounding rocks with which it is in contact varies with a number of factors. For one thing, it naturally varies with the size of the intruded mass; it also varies with the nature of the vapors which are given off, as described under pegmatite formation. Another factor is the nature of the rock that is being affected, some kinds being more susceptible than others, and it also depends on the attitude of these rocks, that is, in the sedimentary beds, on the position of the planes of stratification with reference to the igneous mass. All of these are important features and each deserves separate treatment in order that the subject may be fully understood. In general, the most noticeable field evidence of the exomorphic effect is a baking, hardening, or toughening of the surrounding rocks. It not uncommonly happens as a result of this process that the rocks thus hardened resist erosion better than the intruded mass or the unchanged enveloping rocks, and consequently give rise to distinct projecting topographic forms. This is admirably illustrated in the Crazy Mountains of Montana, where the resistant rocks of the contact zone give rise to a series of high ridges and peaks which encircle a more eroded mass of intruded igneous rock and rise sharply from a sloping plain of soft unchanged shales and sandstones. It may thus occur that a dike and the surrounding beds are lowered more rapidly by erosion, while the contact walls on either side are left projecting as two parallel ridges.

The mineralogical effect is that, in general, where the agencies have made themselves most strongly felt there is a transformation of the rocks. This is produced by an interchange of the molecules within short distances, whereby former chemical combinations are broken up and new ones formed. In mass, that is, in sum total, the chemical composition of the altered rock generally remains the same, except that volatile compounds, water, carbon dioxide, organic matter, etc., are driven out, and in some cases, volatile components, fluorine, boron, etc., may be added by the mineralizing vapors from the igneous mass.

Modes of Occurrence. The widest and most pronounced contact zones as a rule occur about the great intrusive stocks and batholiths. This is most natural, since the vast size of the igneous body supplies heat and vapors for a great length of time. Around many stocks and batholiths, contact zones a mile and even more in breadth have been formed. After those found in such situations, perhaps the most striking are seen about old volcanic necks. The breadth and intensity here often seem disproportionate to the size of the igneous mass, but this is to be explained by the fact that the necks represent conduits through which fresh supplies of highly heated matter have been successively passing. This renewal of matter in the conduit may thus induce a superadded effect. In such places there may be no endomorphic effect of cooling on texture as described above: the conduit walls are so highly heated that the texture of the igneous rock remains the same up to the very contact wall.

In the case of dikes, considerable variations may be seen; small dikes exert an effect for only a few inches or even less, while large ones may cause changes for many yards on either side. Again, some dikes have served as conduits for magma passing up through them into larger intrusions above, feeding sills or laccoliths or giving rise to extrusive outflows. About them the metamorphism will naturally be greater, other things being equal, than where a fissure was filled by a single charge of magma which immediately came to rest. For this reason the metamorphism induced by intrusive sheets and laccoliths is generally inconsiderable, since they also represent a single charge of magma into the rocks about them, which is not renewed. Immediately at the contact and for a few feet or yards beyond, the rocks may be altered, but the effect dies out within a short distance, except near very thick sills and large laccoliths. With extrusive lava flows, a small amount of baking or hardening of the rocks and soils on which they rest is often seen.

Position of the Rocks. It is a common thing to observe that the width of the contact zone varies considerably from place to place about the intrusive mass. This variation may be due to underground irregularities in the igneous rock body, a wide extension of the zone pointing to a corresponding extension of the mass below, as illustrated in Figs. 71 and 72. In the stratified rocks the position or attitude of the planes of stratification to the intrusive mass is also important. Thus in Fig. 73 the beds at *B* dipping into the mass of granite *C* tend to have their bedding planes and joints opened by the upward movement of the magma, and their position is such as to facilitate the entrance and wide extension of the vapors and heat, thus producing a broad contact zone. On the side *A*, on the contrary, the conditions are just the reverse of this and a much narrower contact zone is the result.

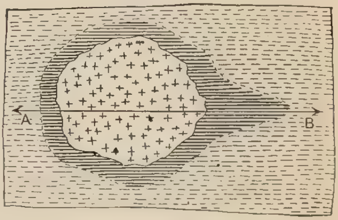


Fig. 71. Ground Plan or Map of an Intruded Stock and its Contact Zone

Fig. 72. Vertical Section along Line A — B in Fig. 71

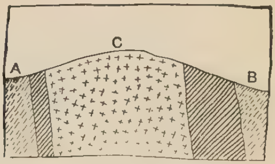


Fig. 73. Section showing width of Contact Zone depending on Position of Beds

Effect on Different Kinds of Rocks. In a general way the most notable effects are produced on sedimentary rocks, — the sandstones, limestones, clay shales or slates, and their various admixtures. On pure quartz *sandstones* the effect is relatively slight, though for short distances and in the innermost zone of most intensive action they are sometimes hardened into quartzites. Pure *limestones* are recrystallized and changed into *marble,* not infrequently in large masses and over considerable distances. The most notable effects are produced when the limestones are impure, containing quartz sand and clay mixed with them. In such limestones the SiO_2 drives CO_2 out and the carbonates are changed to silicates. If the limestone is dolomitic, hence containing magnesia, the results are more complex. Some of the simpler of these changes may be readily shown by equations which represent the chemical changes involved.

$$\overset{\text{Calcite}}{CaCO_3} + \overset{\text{Quartz}}{SiO_2} = \overset{\text{Wollastonite}}{CaSiO_3} + \overset{\text{Carb. diox.}}{CO_2}$$

$$\overset{\text{Dolomite}}{CaMg(CO_3)_2} + \overset{\text{Quartz}}{2\,SiO_2} = \overset{\text{Pyroxene}}{CaMg(SiO_3)_2} + 2\,CO_2$$

$$\overset{\text{Calcite}}{3\,CaCO_3} + \overset{\text{Kaolin}}{H_4Al_2Si_2O_9} + \overset{\text{Quartz}}{SiO_2} = \overset{\text{Garnet}}{Ca_3Al_2Si_3O_{12}} + \overset{\text{Carb. diox.}}{3\,CO_2} + \overset{\text{Water}}{2\,H_2O}$$

$$\overset{\text{Calcite}}{CaCO_3} + \overset{\text{Kaolin}}{H_4Al_2Si_2O_9} = \overset{\text{Anorthite}}{CaAl_2Si_2O_8} + CO_2 + 2\,H_2O$$

In some contact zones the rock is thus entirely changed into silicates or mixtures of them, but usually it consists of impure marble or altered limestone containing the minerals aggregated into lumps or bunches. Carbonaceous material which may be present is often changed into graphite. In addition to those minerals mentioned, a variety of others, the origin of which is due to the mineralizing vapors given off by the igneous rock, may also be formed, such as mica (phlogopite), chondrodite, hornblende, vesuvianite, epidote, tourmaline, etc. In these minerals the main materials are those already in the rock; but the vapors furnish the volatile components: the hydroxyl, boron, fluorine, etc., needed for their composition. Such minerals furnish transitions to the more typical pneumatolytic contacts mentioned below. It should not be forgotten also that many of these minerals contain oxide of iron, ferrous or ferric or both, and this may come from the limonite or other hydrated iron oxides mixed in with the impure marly beds and deposited with the other material at the time of their formation.

In some contact zones, however, iron has been added by the hot gases expelled from the magma; it was probably carried there in the form of a volatile chloride or fluoride. Perhaps, of the minerals mentioned, garnets, pyroxenes, and vesuvianite may be taken as among the most typical of such occurrences in altered limestones. Many instances of such contacts are known in various parts of the world and some of them have become famous for the variety and beautiful crystallizations of the minerals which they afford and which are to be found in all mineral cabinets.

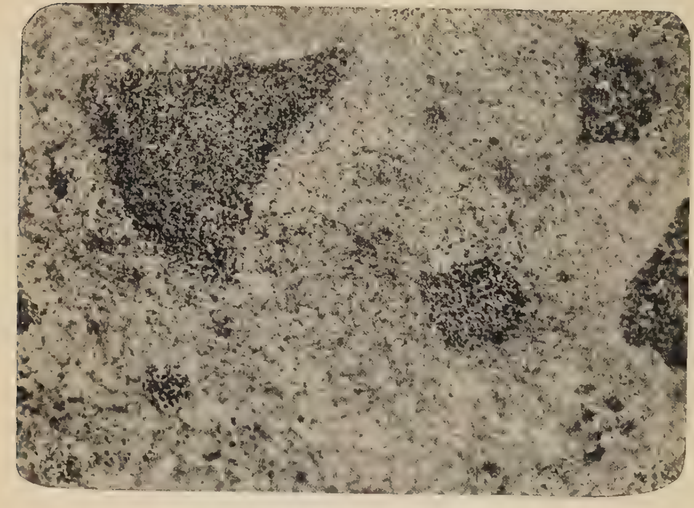
In *clay shales* and *slates* variable effects are produced, but usually ones that are well marked and characteristic. While such rocks consist mostly of microscopic fragments of quartz, granules of clay, mica, etc., there is considerable variability in their composition and accordingly a variability in the result of the metamorphism. Sometimes they are baked into a hard aphanitic rock with conchoidal fracture, of a black or very dark stone color, called *hornfels*, or *hornstone*, which closely resembles trap or basalt. Sometimes they are like the hornfels in hardness, texture, and fracture, but differ in color, being of a light gray to green-gray or greenish and are known as *adinole.*

Where the beds are richer in kaolin, a mineral, andalusite, is likely to develop according to this formula:

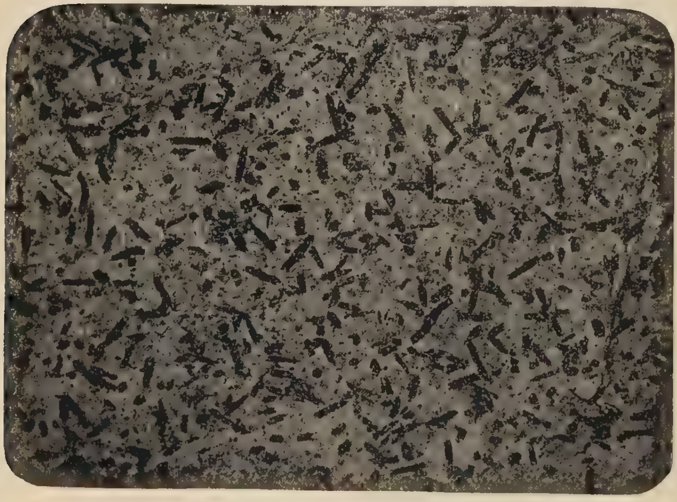
$$\begin{array}{ccccccc} \text{Kaolin} & & \text{Andalusite} & & \text{Quartz} & & \text{Water} \\ H_4Al_2Si_2O_9 & = & Al_2SiO_5 & + & SiO_2 & + & 2\,H_2O \end{array}$$

At the contact a rock composed largely of this, often in recognizable grains and crystals, and mixed with a brown biotite in glimmering specks, forms a granular rock, generally dark in color and much resembling an igneous rock in texture. All visible evidence of bedding of sedimentary character is lost. This rock is termed an *andalusite hornfels.* Farther from the contact the hornfels begins to lose its granular texture; it becomes more schist-like or perhaps slaty and is dotted with the andalusite prisms. These very frequently gather up the dark organic matter of the rock and arrange it within themselves in

PLATE 12.



A. INCLUSIONS IN GRANITE.



B. FRUCHTSCHIEFER.

the manner characteristic of this mineral. They then appear dark on a lighter background, as seen in Fig. B, Plate 12. This variety of rock is known as "Fruchtschiefer" (fruit schist) by the Germans. The rock has much the character of a fine-textured mica-schist.

Still farther from the contact the effects of metamorphism are less and less marked, and the beds show more and more of their original sedimentary nature; in this part the most evident effect is a spotting of the shales or slates as a result of the collection of organic matter or minerals into more or less well-defined points or knots. Such a development of knots is one of the most characteristic features of moderate contact metamorphism and, when encountered in the field, should always lead to search for more intensive effects and the possible nearness of intrusive igneous rock bodies. The latter may, of course, be below and not yet exposed by erosion.

Just as all kinds of variations between sandstones, limestones, and shales are found in nature, so do the different varieties of rocks produced by contact metamorphism, as described above, vary and grade into one another.

In the nature of things, the already existent *igneous rocks* are less altered by the contact metamorphism of following intrusions than the sedimentary ones. This is particularly true of the granites and other very feldspathic rocks. The ferromagnesian ones, those containing feldspars rich in lime, and especially those composed chiefly of pyroxene, show in places considerable effects. The pyroxene is converted into hornblende and the rock becomes an amphibolite and even in places a hornblende schist.

Pneumatolytic Contacts. It was mentioned above, in connection with the changes observed in limestones, that the origin of some of the minerals that appeared was due to the mineralizing vapors given off from the igneous mass. In some contact zones the rocks may be converted into masses of such minerals, testifying to the abundance and energetic action of the excluded vapors. Such minerals as tourmaline, topaz, fluorspar, vesuvianite, mica (muscovite), etc., which contain hydroxyl, fluorine, and boron, are characteristic of these occurrences. The masses thus formed are not continuous and regular around the contact but appear here and there, especially near fissures, sometimes as isolated areas in the other rocks, sometimes in large, sometimes in smaller lumps and masses, as determined by the irregular escape of the gases from the consolidating magma.

Contact Zones and Ore Bodies. The contact zones of igneous rocks are especially favorable places for the deposition of certain kinds of ores, both because of the passage of the vapors and the movement of heated solutions in such zones, and because the chemical composition of the rocks themselves causes them to react with the solutions. As a result of this process many valuable deposits of the ores of copper and iron have been formed from magmatic gases in such contact zones. They are termed contact-metamorphic ore deposits; they are generally restricted to limestones on account of the ease with which limestone reacts with the magmatic gases and causes them to deposit the copper, iron, and other substances that they are carrying. Any adequate treatment of this subject would carry us far beyond the limits of this work and further information should be sought in those treatises which deal with the origin of ore deposits.

Classification of Igneous Rocks

Introductory. There is probably no subject in the domain of natural science concerning which there has been and is today less agreement than in the classification of igneous rocks. The reason for this is that there are no distinct boundary lines drawn by nature itself. The igneous rock masses of the Earth possess certain features which may be used to distinguish and discriminate them, one from another, such as their geologic mode of occurrence, their mineral composition, their texture, and their chemical composition. A very brief inspection serves to show, however, that in each of these features gradations exist without hard and fast lines. If we classify igneous rocks according to mode of occurrence and divide them into intrusive and extrusive rocks, then, for example, it is clear that every lava flow is (or was) prolonged into depths below by an intrusive continuation in the form of a dike or volcanic neck. We should have to separate the intrusive from the extrusive at some point by an arbitrary plane; above this plane the rock would receive one name, below it another, though it is clear that the material just above and that just below would be absolutely alike. The same is true when we consider the other features of rocks mentioned; they are found to grade into each other mineralogically, chemically, and texturally, and where lines are drawn it must be done arbitrarily. It is due to these facts that so much diversity of opinion has existed regarding the classification of igneous rocks, some laying stress on one feature, some on another. By general consent among petrographers, especially since the use of the microscope has served to reveal the composition of the aphanitic rocks, a large number of different kinds of igneous rocks are recognized, based primarily on the kinds and relative quantities of their component minerals and on their texture; but as to the manner in which these recognized kinds shall be grouped in a classification there is, as stated above, wide diversity of opinion. It is not advisable to discuss this subject further; but it should be clearly understood at the outset that, whatever method of classification of igneous rocks is used, the boundary lines are necessarily artificial, and in many cases just where a rock should belong must be a matter of opinion, which each must decide for himself.

Older Megascopic Classification. Before the microscope came into use in studying rocks, they were naturally divided into two groups: those whose component mineral grains were large enough to be seen and recognized, and those which were too fine-grained to permit this. The former group was divided into different kinds according to the mineral varieties composing them, and the latter according to the color, texture, luster, and other physical properties they presented. In this manner, by common usage, a megascopic classification, extremely useful for geologic and common purposes, came about, which gave rise to such terms as granite, diorite, porphyry, greenstone, basalt, etc.

Effect of the Microscope. When the microscope came into use it was discovered that the aphanitic rocks could be studied and their component mineral grains determined nearly as easily as the coarse-grained ones, and the result of these studies showed that a vastly greater diversity existed among them than had been suspected. The microscope also revealed that the coarser grained rocks contained many minerals not previously known to exist in them, while it showed great variations among the minerals known to compose them, as well as differences in texture, etc. To express these differences among the rocks and to connote the ideas that these differences engendered, not only have a whole host of new rock names arisen, but the old megascopic terms have been defined and redefined by various authorities, until they have nearly all lost their original significance.

This has been an unfortunate phase of the history of the development of petrography as a science, because these former megascopic or field names, as we should term them now, served a very useful and necessary purpose, which the more exact and scientific nomenclature of modern petrography cannot serve. The person who desires to deal with rocks and name them from the megascopic, field point of view, such as the field geologist, the engineer, the architect, etc., is left without any equipment for doing so. A single illustration will suffice. The old term granite meant any granular igneous rock and then later one composed of quartz and feldspar. Now, according to the usage of modern petrographers, a rock is not a granite unless the feldspar is chiefly alkalic, while if it contains dominantly soda-lime feldspar, it is termed a quartz diorite. This is a distinction that ordinarily cannot be made without microscopic study.

The redefinition and specializing of these useful general field terms has very much the same result as if the botanists had redefined such terms as bush, tree, vine, shrub, etc., and had made them the names of particular species or genera, so that if tree, for instance, were properly used, it would designate only oaks, or even *Quercus alba.*

In the meantime in the world at large, where rocks are commercially dealt with, as in mining, architecture, etc., the use of rock names in the old way has gone on quite regardless of the petrographers, but the geologist or engineer who has endeavored to keep up with the development of the science and use its terms megascopically has carried an ever-increasing load until finally he has been compelled to become a petrographer or else give up in large part any independent use of rock names. Without doubt it is largely due to this fact that every advance in the definiteness and completeness of petrographic scientific nomenclature has raised a wave of protest among geologists.

Present Need in Classification. It is clear that the parting of the ways has long been reached, and it ought to be definitely recognized that the further development of petrology and of the classification and nomenclature of rocks from the scientific standpoint must be left largely to petrographers, while those who have occasion to deal with them in the purely megascopic manner must have a method of classification and a set of terms of a somewhat different scope and usage. They must in large measure revert to that which was in vogue before the microscope came into use.

It matters little whether or not such a classification is completely based on all the principles underlying scientific petrology which the study of rocks has revealed; to be useful it must be practical, and to be practical it must be based entirely on the evident megascopic characters of rocks, such as can be seen by the eye or pocket lens or be determined by simple means at everyone's command.

Classification used in this Work. As it is the object of this work to treat rocks from this point of view, the following method of classification has been adopted.* First, the rocks are considered according to their texture and from this it will be found that they divide themselves naturally into three classes, *grained,*† *aphanitic,*‡ and *glassy.*

I. *Grained Rocks,* or *Phanerites.* By this is meant those rocks of which the component mineral grains are large and distinct enough to be seen and recognized by the eye alone or with the lens. No hard and fast line can be here drawn as to the size of grain; it will vary with the kind of minerals, their association together, and on the experience and skill of the observer. In general it may be said that it includes rocks whose average size of grain is as large as or larger than that of ordinary loaf sugar.

II. *Aphanitic Rocks,* or *Aphanites.* This class includes those rocks that are nearly or wholly of stony appearance and texture but the minerals of which cannot be determined, because they are too minute. These rocks may, because of their homogeneous appearance, seem to be composed of a single substance, but they are generally microcrystalline aggregates of more than one mineral.

III. *Glassy Rocks.* This class includes those wholly or in part made up of glass, as shown by their vitreous or pitchy

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* This is essentially that proposed by the author and several other petrographers. "Quantitative Classification of Igneous Rocks," by Cross, Iddings, Pirsson, and Washington, University Chicago Press, 1903, p. 180.

† The term "grained" is here used instead of "granular" for two reasons. First, because granular (from granule — a little grain), strictly speaking, means fine-grained, while the rocks included may be coarse, medium, or fine-grained. Second, because granular is used by many petrographers in a technical way as an equivalent to "even-granular" and opposed to porphyritic, while grained rocks may be either. *Phanerocrystalline, macrogranular, megagranular,* etc., have much the same meaning but it is better to use a simple English word than a compound Latin or Greek one.

‡ "Dense" is often used in geology as a synonym for "aphanitic," but this usage cannot be defended by an appeal to the dictionary. Dense is defined there to mean closely set, crowded, compact. A porphyry might be dense with phenocrysts.

luster, conchoidal fracture, and other characters and appearance.

Subdivisions of Class I. The igneous rocks having been divided into classes on the basis of texture, it now remains to show on what grounds these classes can be further subdivided and the individual kinds of rocks, from the megascopic standpoint, obtained. This is done, as already suggested, in the *even-* and *porphyritic-grained* rocks by considering their mineral composition. First we may broadly divide them into two main groups.

a. Rocks in which the feldspars or feldspars and quartz predominate: feldspathic rocks.

b. Rocks in which the ferromagnesian minerals (pyroxene, hornblende, olivine, etc.) predominate: ferromagnesian rocks.

As a rule, the rocks of the first group are light-colored, white, red, or gray, but this is not an absolute rule since the feldspars are sometimes very dark from an included pigment. In general, the rocks of the second group are dark in color to black, but this is also not an invariable rule since some, like those composed wholly of olivine, are rather light.

The first group *a* may be further subdivided on the basis of the relation of quartz to the feldspars and on the nature of the feldspar present, whether orthoclase or plagioclase. Those which contain an appreciable amount of quartz with orthoclase fall in one division and are termed *granite* when even granular in texture, and *granite porphyry* when of porphyritic texture; while those in which quartz is absent or is present in inappreciable quantity are called *syenite* and *syenite porphyry* respectively. Further division of the feldspathic rocks into varieties on the basis of particular mineral characters will be considered in the description of them in the succeeding chapter.

The second group *b* is subdivided on the basis of the relation of the feldspars to the ferromagnesian minerals, into those which contain feldspar subordinate in amount to the ferromagnesian minerals, and those in which it is wanting. Thus we have as follows:

Rocks with predominant ferromagnesian minerals; feldspar subordinate.

Rocks consisting wholly of ferromagnesian minerals.

Rocks composed chiefly of ferromagnesian minerals are termed gabbro; the feldspar in them is generally a calcic plagioclase.

Porphyries occur in the group of ferromagnesian rocks but they are relatively of less importance than in the feldspathic rocks; they are treated in the descriptive part. Rocks in which ferromagnesian minerals, other than hornblende and pyroxene, predominate over feldspar are known, but are of little practical importance in a megascopic scheme of this character and are therefore omitted. They will be mentioned later.

The last subdivision, in which the rocks consist wholly of ferromagnesian minerals, is divided according to the kinds of these minerals present. The most common and prominent mineral is pyroxene but it is usually associated with olivine and the rock is termed *peridotite.* This is the most common member and may be used as a general term for these ultrabasic rocks, as they are sometimes called. If olivine is absent and the rock consists wholly of pyroxene it is *pyroxenite;* if of hornblende, *hornblendite.* Varieties are described under peridotite. *Porphyries* rarely occur in the peridotite group and are of no practical importance.

In summation, in considering the classification of the group of grained rocks the constituents of which are determinable, one should consult what has been said regarding the chemical composition of igneous magmas and the variations in mineral composition, beginning on page 140. It is not possible, however, to classify them entirely for megascopic purposes by the diagram given on page 144, for, in general, we cannot discriminate between the different kinds of feldspars. Thus the rock there shown as quartz diorite must be classified under the head of granite, while, as compared with the diagram, the diorite and gabbro mentioned above broadly overlap. Still, in a general way, bearing these exceptions in mind, the classification, distinguishing between the feldspathic and the ferromagnesian rocks, brings out the ideas there expressed. The rocks of this class are nearly always intrusive, rarely extrusive.

Subdivisions of Class II. In considering the second class of rocks, II, the texture of which is so fine that the mineral grains cannot be determined, we have little upon which to base a field classification except the color. They are thus divided into two groups, the light-colored and the dark-colored. Of course if the rock is either white or black there can be no difficulty in assigning it to one or the other of these two divisions, but all gradations of color exist and it is often a matter of pure choice to which a particular rock should belong. Evidently some closer definition of the terms is needed. We may supply this as follows: The term *dark* includes rocks that are *very dark gray*, *very dark green*, or *black;* all other colors, *white*, *red*, *purple*, *yellow*, *brown*, light and medium *gray*, light and medium *green* are *light*. The light-colored rocks are known as *felsites*, while dark rocks are *basalts*. The division thus made also expresses in a general way an important fact concerning their composition, for the felsites are derived from magmas which, if the physical conditions were such as to produce coarser-grained rocks, would crystallize as granites and syenites. On the other hand, the basalts represent the diorites, gabbros, and peridotites in fine-textured forms. While many exceptions will be found, this general rule holds true and the light rocks as defined above are chiefly feldspathic, the dark are mainly ferromagnesi

While the rocks of this group are often of homogeneous texture and aspect, they are more often porphyritic. We then have *felsite porphyry* and *basalt porphyry* respectively, according to the color of the groundmass. It has also been suggested that these porphyries may be called *leucophyre* (light-colored porphyry) and *melaphyre* (dark-colored porphyry), respectively.* Further subdivisions of these porphyries can be made according to the minerals that occur as the prominent phenocrysts. Thus we might have *quartz felsite porphyry, feldspar felsite porphyry, hornblende felsite porphyry* or *quartz leucophyre, feldspar leucophyre,* and *hornblende leucophyre,* and similarly we have *augite basalt porphyry, mica basalt porphyry, feldspar basalt porphyry* or *augite melaphyre, mica melaphyre,* and *feldspar melaphyre.* Many combinations of this kind can be made, but the above will suffice as examples. Some of the rocks of this class are intrusive, some are extrusive.

However, it is often possible to subdivide the felsite porphyries according to the kinds of rocks that are commonly recognized in current geologic literature. The felsite porphyry group is so broad as to include, as shown in the tabular classification on page 205, rhyolite, trachyte, latite, dacite, and andesite. These various rocks can be distinguished with sufficient accuracy for megascopic purposes on the basis of the kind of phenocrysts present. If the felsite porphyry contains phenocrysts of quartz and feldspar it is either a rhyolite or a dacite. If most of the feldspar phenocrysts are unstriated, thus indicating orthoclase, it is a rhyolite; if most of them are striated, indicating plagioclase, it is probably a dacite. If the salic phenocrysts are all orthoclase, the rock is a trachyte; if considerable plagioclase is associated with the orthoclase, the rock is a latite; and if they are all plagioclase, it is an andesite. Biotite and hornblende, singly or together, may occur as phenocrysts along with the quartz and orthoclase in rhyolite; biotite, hornblende, and pyroxene, singly or together, are common as phenocrysts in the other rocks. Thus we may have hornblende dacite, pyroxene andesite, hornblende-pyroxene andesite, etc.

The distinction between rhyolite and dacite, and between trachyte, latite, and andesite cannot always be made megascopically, since it depends on the kind of feldspar present, and in some rocks the feldspar can only be determined by optical

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* Quantitative Classification of Igneous Rocks, p. 184.

means. However, it is a distinction that should always be attempted in the field. The principle according to which the felsite porphyries are subdivided is that they carry as phenocrysts those minerals that make up the coarse-grained rocks (phanerites) of which they are the effusive equivalents.

Subdivisions of Class III. The rocks of the third class, III, those wholly or partly of glass, are distinguished by their glassy or resinous luster and want of stony texture. They may be classified as follows:

OBSIDIAN, luster strong, bright, glassy; color usually black, sometimes red, more rarely brown or greenish.

PITCHSTONE, luster resinous or pitch-like; colors various, as above, but black less common.

PERLITE, glassy rock with perlitic structure that is produced by small spheroidal fractures; usually gray in color.

PUMICE, highly vesicular glass (see page 159), usually white or very light-colored.

Any of these may be porphyritic or not; though cases of porphyritic pumice are much less common than in the other three. When porphyritic, a general name for them is *vitrophyre* (glass porphyry) and different varieties may be distinguished, as in the porphyries of the class above, according to the kind of predominant phenocrysts; thus *quartz vitrophyre, feldspar vitrophyre*, etc. The rocks of this class are practically wholly confined to lavas.

Class IV. In addition to the three main classes of igneous rocks described above, we may add as an appendix in a fourth class, IV, the fragmental material thrown out in volcanic eruptions and already mentioned on page 139 as *tuffs* and *breccias.*

Such material serves as a connecting link between the sedimentary and igneous rocks. For, as it falls through the air, it becomes assorted as to size, and successive outbursts thus produce rough but distinct bedding. Or it may fall into water and become perfectly stratified. Falling on the land, it may cover vegetation and contain fossil imprints of plants, leaves, etc.; or if into water, of marine organisms. Hence if we classify volcanic ash beds as igneous rocks, we cannot say that a distinguishing feature of igneous rocks is that they never contain fossils. See remarks on page 129.

Classification Tabulated. The classification which has been adopted and described in the foregoing may now be shown, for convenience of reference, in tabulated form on the following page.

Classifications based on Microscopic Research. In the classification previously described, the color and texture of rocks play a prominent part, and mineral composition can be used only in an approximate manner. But where rocks are studied in thin section under the microscope, texture becomes of much less importance; all of the minerals and their exact characters can be discovered and their relative proportions made out. In this more exact work the kinds of rocks that are recognized by petrographers are based primarily on the kinds, and to some extent on the relative proportions, of the component minerals. This makes a great number of kinds of rocks which have been named. Generally they are grouped, first, according to minerals, and second, according to texture; some petrographers lay weight also on their mode of occurrence, whether extrusive or intrusive, while others add to this the genetic relations or groupings which the rocks show in nature. Classifications have also been proposed in which the chemical composition of the rocks plays the most prominent part.

Quantitative Classification. In 1903 several petrographers, including the author, proposed an exact scientific classification of igneous rocks based on their chemical composition, expressed, however, in terms of minerals of definite composition, called standard minerals. For this purpose a chemical analysis of the rock is necessary but, where this cannot be obtained, an approximately correct result may be achieved by measuring the minerals under the microscope, computing from their measurements their relative bulk and weight, and, their composition being known, reckoning from this the chemical composition of the rock as a whole, as if obtained by chemical analysis.

The chemical composition is then recalculated, according to a set plan, into the relative amounts of standard minerals.

MEGASCOPIC CLASSIFI

		a. Feldspathic r		
		Orthoclase		Orthocl
		With quartz	Without quartz	With quar
I. PHANERITES (grained rocks; constituents recognizable) Intrusive	Nonporphyritic	GRANITE Aplite Pegmatite	SYENITE Nephelite Syenite	QUARTZ MONZONIT and GRANODIO
	Porphyritic	GRANITE PORPHYRY	SYENITE PORPHYRY	QUARTZ MONZONI PORPHYR and GRANODIO PORPHYR
II. APHANITES (All constituents except phenocrysts unrecognizable) Extrusive or intrusive near Earth's surface	Porphyritic	RHYOLITE	TRACHYTE	
	Nonporphyritic			
III. GLASSES (Composed wholly or largely of glass) [illegible]	Nonporphyritic			OBSIDIAN,* P
	Porphyritic			V
IV. FRAGMENTAL IGNEOUS MATERIAL Extrusive				TI

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* Most obsidians

IGNEOUS ROCKS

y light-colored			b. Ferromagnesian rocks, generally dark-colored	
clase	Plagioclase		With plagioclase	Without plagioclase
ut quartz	With quartz	Without quartz		
ZONITE	QUARTZ DIORITE	DIORITE	GABBRO Dolerite (intermediate in grain size between basalt and gabbro)	PERIDOTITE PYROXENITE HORNBLENDITE
ONITE PHYRY	QUARTZ DIORITE PORPHYRY	DIORITE PORPHYRY	GABBRO PORPHYRY	
	DACITE	ANDESITE dark	BASALT PORPHYRY	
✓			BASALT	
lite, Pumice.				
sidian porphyry and Pitchstone porphyry)				
CIAS (volcanic ash, etc.)				

ed.

These standard minerals are divided into two main groups: one characterized by the presence of alumina and silica, such as feldspars, nephelite, corundum, and quartz, but without iron or magnesia; the second characterized by iron and magnesia but without alumina, such as olivine, diopside, hypersthene, ægirite, and iron ores. The complex ferromagnesian minerals which contain alumina, such as hornblendes, biotite, augite, etc., are not treated as standard minerals because it is better to consider them as compounds of simpler molecules of the two preceding groups. The first of these is called the *salic* (Si and Al), the second the *femic* (Fe and Mg) group of standard minerals, and the composition of the rock computed in quantities of them is called its *norm*, which may thus, when hornblende or biotite is really present in it, differ considerably from its actual mineral composition or *mode*.

All igneous rocks may be expressed in salic and femic minerals. According to the relative amount of each group as compared with the other, they are divided into five classes:

persalane, nearly or entirely composed of salic minerals

$$(\text{sal} : \text{fem} > 7 : 1);$$

dosalane, mostly salic

$$(\text{sal} : \text{fem} < 7 : 1 > 5 : 3);$$

salfemane, equal or nearly equal quantities of each

$$(\text{sal} : \text{fem} < 5 : 3 > 3 : 5);$$

dofemane, mostly femic minerals

$$(\text{sal} : \text{fem} < 3 : 5 > 1 : 7);$$

and lastly *perfemane*, nearly or entirely femic

$$(\text{sal} : \text{fem} < 1 : 7).$$

Up to this point it is possible to use this classification in a megascopic manner. The *classes* thus obtained are subdivided into *orders* on the relations of the salic minerals, quartz, feldspars, and feldspathoids (generally nephelite), to one another in the first three classes and on somewhat similar relations among the femic minerals in the last two. More minute consideration of the mineral oxides divides the orders into *rangs* and the rangs into *grads*. The proportions by which they are thus divided are always the same as that by which classes are made.

Further details regarding this and other systems of classification, founded upon results obtained by microscopical research, are to be found in the list of works mentioned on page 11.

CHAPTER VII

DESCRIPTION OF IGNEOUS ROCKS

Grained Igneous Rocks

As explained in the section on classification, the grained igneous rocks are those in which the mineral grains are approximately of equal size and large enough to be identified with eye or lens. Those rocks in which the grain is too fine to permit this will be found under the heading of the aphanitic igneous rocks. The porphyries, in which the major part of the constituent minerals can be distinguished, are described in the following section.

Granite

Composition. Granites are granular rocks composed of feldspars and quartz. Some consist of these minerals alone, but generally there is more or less mica present and often hornblende.

The *feldspar* is the predominant mineral and is readily recognized by its appearance and cleavage. Sometimes only one kind of feldspar is present but generally there are two, mainly orthoclase and, subordinately, some plagioclase feldspar. They may sometimes be distinguished by their colors; if one feldspar is flesh-colored to red while the other is white, gray, or yellow, it is pretty certain that the first is orthoclase, the second plagioclase feldspar. Close inspection of a cleavage surface of the plagioclase with a lens may show the characteristic twinning striations (see page 37), but the grains may be too small to permit this. Granites containing abundant plagioclase are called *quartz monzonites*, according to a usage widely employed in recent years. Those in which the plagioclase exceeds the orthoclase in amount are called *granodiorites* by petrographers and are placed in a separate family, but this cannot be readily done in megascopic determination and they may then be classed as granites.

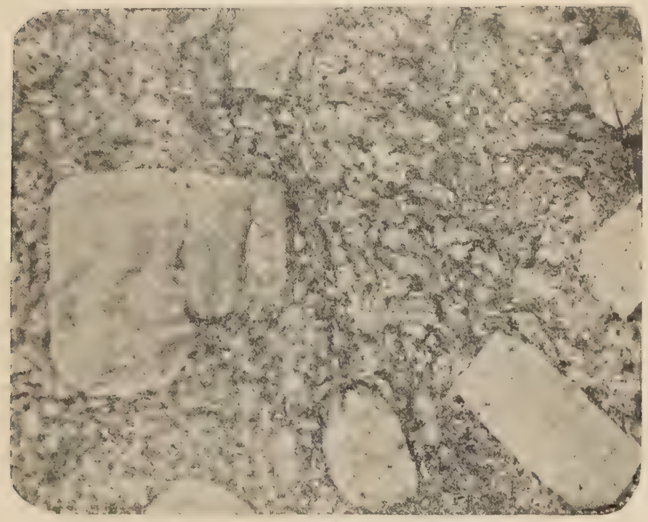
Quartz normally occurs as formless material, filling the interstices between the other minerals, and hence has not its own characteristic crystal shape. The normal color is white to dark, smoky gray; sometimes it is red from included hematite, more rarely a bluish color. In the finer-grained granites the color is usually light or white, especially in those of a sugar granular texture. Quartz is recognized by its glassiness, lack of cleavage, and conchoidal fracture.

The *mica* may be either the light or colorless muscovite or black biotite, or both kinds may be present. Rarely does muscovite occur as the only mica. Hornblende occurs in black to dark green grains or prisms. It is sometimes the only dark mineral but is more usually accompanied by biotite. These are the chief minerals, but if the rock is fairly coarse-grained, close inspection will commonly show occasional metallic-looking specks or grains of magnetite. Sometimes other minerals may be seen: brassy crystals of pyrite, dark red grains of garnet, etc., but these are occasional and are not of importance in determining the rock.

Texture. In ordinary normal granite the texture is an even granular one and alike in all directions through the rock. From this type, sometimes in the same mass, the texture grades insensibly into that of gneiss, which becomes noticeable through the linear arrangement of the components, especially the micas. Thus the rock passes into granite gneiss (primary, or fluxion gneiss). The normal texture is shown on Plate 13. In other granites a tendency may be noted for some of the orthoclase crystals to be larger than the average grain and of more distinct crystal form. In this way the rock becomes porphyritic and when this is pronounced it is the porphyritic granite described below. Often the dark minerals tend to group or bunch together in spots.

PLATE 13.

A. COMMON GRANITE.



B. PORPHYRITIC GRANITE.

Color. The general color of granites depends largely on that of the feldspar and on the proportion of this to the dark minerals. Thus the color shades from white into gray to dark gray, resulting from the mottling by the biotite, etc. Such types are very common wherever granites are abundant, as in New England. More rarely the quartz and feldspar are themselves gray to dark gray and thus determine the color. An example of this is the granite of Quincy, Mass., largely used as a building stone. Another very common type of coloring is one in which the rock is flesh-colored, pink to red and even deep red. Such red granites are found in Maine, Missouri, Colorado, Scotland, and other localities and are largely quarried and used for building.

Varieties. The varieties of granite depend on the relative proportions of the light and dark minerals, the color, and the texture. The relative amount of the biotite (or hornblende) to the quartz and feldspar may vary widely; the biotite or hornblende may be entirely wanting or they may be present in large amount and make the rock quite dark. Such extreme cases are less common. The grain may become as coarse as large peas or even coarser. These variations, combined with those in color, produce distinct types of granite which have often received local names. Some other varieties are described in following sections.

Porphyritic Granite. As mentioned above, the feldspar may occur partly in large distinct crystals or phenocrysts. Crystals as much as two and three inches or more in diameter may be scattered through the granite, but because these phenocrysts are as a rule somewhat sparsely distributed, it is the custom to speak of such a granite as a porphyritic granite. The feldspar phenocrysts are crystals of orthoclase and have the forms shown under feldspar, page 34. Reflection of light from the cleavages of these on the rock surface often shows them to be in twin halves, due to Carlsbad twinning. An illustration of this type of granite is seen on Plate 13. Such rocks occur in New Hampshire and other localities in New

England, in Colorado, in the Sierra Nevada Mountains, in England (Dartmoor and elsewhere), in the Black Forest region, and in other places.

Chemical Composition. The bulk compositions of a few selected granites are shown in the analyses given here to illustrate the kind of magma from which such rocks have crystallized.

ANALYSES OF GRANITES

	I	II	III	IV	V
SiO_2	77.6	74.4	71.2	68.0	66.3
Al_2O_3	12.0	13.1	13.7	17.2	16.0
Fe_2O_3	0.6	0.7	1.7	3.1	1.8
FeO	0.9	0.9	1.0	0.4	1.9
MgO	trace	0.4	0.8	1.2	1.1
CaO	0.3	1.3	2.3	2.9	3.7
Na_2O	3.8	2.6	3.6	3.2	4.1
K_2O	5.0	6.1	3.8	3.9	3.5
H_2O	0.2	0.3	1.7	...	0.5
XyO*	0.2	0.4	0.2	...	0.9
Total	100.6	100.2	100.0	99.9	99.8

* XyO = small quantities or traces of other oxides.

I, Hornblende Granite, Rockport, Mass.; II, Biotite Granite, Crazy Mountains, Montana; III, Granite, Conanicut Island, Rhode Island; IV, Granite, Kirkcudbright, Scotland; V, Granodiorite, Mariposa County, California.

The large percentages of silica, alumina, and alkalies explain the predominance of feldspars and quartz. With the increasing lime in the last two analyses, the alkalic feldspars give place in precedence to plagioclase; the increasing iron and magnesia show increasing amounts of the dark minerals; coincidently with this the silica falls; the amount of free quartz is less and such rocks approach the next class, the syenites.

Physical Properties. The *specific gravity* of granites varies with the kinds and relative amounts of the component minerals; from 2.61 to 2.75 is the ordinary range, those containing more ferromagnesian minerals being the heavier. The average weight of a cubic foot of granite is about 165 pounds. Usually the porosity of such granites as are quarried for building purposes is very small, the percentage of water absorbed, compared with the weight of the dry rock, being about 0.15 of one per cent. Thus a cubic foot of average granite if completely saturated would absorb about 4 ounces of water. The strength of granites in resistance to crushing is very great and probably far greater than any load they would be called upon to bear in architectural work. A series of Wisconsin granites tested by Buckley showed crushing strengths varying from 15,000 to 40,000 pounds per square inch; some of these were very high, and from 15,000 to 20,000 is perhaps the average. As the pressure at the base of the Washington Monument is 342.4 pounds per square inch, it will be seen that there is an ample reserve in most cases.

Uses of Granite. As is well known, on account of its great strength and durability, granite is extensively used for architectural purposes. Its pleasing colors and the high polish it takes cause it to be employed as an ornamental stone in interior work, in monuments, etc. In one respect, however, many granites have a defect which somewhat impairs their value for use in buildings in large cities. This defect is that they do not resist fire well, but crack, scale, and sometimes crumble under great heat. One reason for this is that the quartz grains are very commonly filled with minute bubbles containing water or liquid carbonic acid gas (CO_2) or both.* They are so minute that they are often only to be detected with high powers of the microscope in thin sections but they may absolutely swarm in the quartz and constitute an appreciable fraction of its bulk. They represent material taken up or included at the time of its crystallization. Under the action of heat the pressure on these sealed crystal flasks becomes enormous; each quartz grain becomes, so to speak, a veritable tiny bomb and eventually

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* The different rates of expansion of quartz and feldspar are another cause.

it must crack in all directions and crumble and thus injure the strength and resisting capacity of the stone. Probably the large coefficient of expansion of quartz at high temperatures is the chief cause of the poor fire-resistive capacity of granite. Feldspars practically never contain liquid inclusions, like quartz, nor do the other ordinary rock minerals, so that rocks like syenite or diorite, in which quartz is absent or only sparingly present, make, in respect to resisting fire, much better stone than granite.

Jointing in Granite. Granite tends to a block jointing on a large scale in the great stocks. There generally tend to be three distinct sets of joints, two of which approximate to the perpendicular, the third to the horizontal. Sometimes these are nearly at right angles, producing cubes, more often at angles which make rhomboidal blocks. Sometimes the horizontal one is most pronounced and the mass has a sheeted or layer-like character suggesting bedding. In dikes the joints are much more numerous and the mass breaks into small blocks, plates, etc. This jointing of granite is a matter of much importance in the work of excavation, in mining, tunneling, quarrying, etc., in facilitating removal of material, but it also explains why every granite mass is not suited to furnish material in blocks of sufficient size for constructional purposes. Quarries like those in Finland, in the so-called Rapakiwi granite, from which the base, a cube of 30 feet, and the shaft, 100 feet high by 15 feet in diameter, of the Alexander monument in Leningrad were taken, and those in Egypt from which the great obelisks were cut, are not common. Compare Plate 10.

Erosion Forms of Granite. The jointing of granite largely conditions the work of erosive agencies on the mass but the topographic forms produced also depend greatly on the severity with which these agencies act. In the high mountain chains and wherever they are very energetic, spires, needles, and castle-like forms are produced; but in the lower massive and older ranges and where glaciation has been pronounced, the granite stocks form more smoothly modeled, rounded, or dome-

PLATE 14.

A. EROSION OF GRANITE IN THE HIGH ALPS.

(After Duparc.)

B. EROSION OF GRANITE IN OLD AND LOW MOUNTAIN REGIONS, STONE MOUNTAIN, GEORGIA.

(Georgia State Geological Survey.)

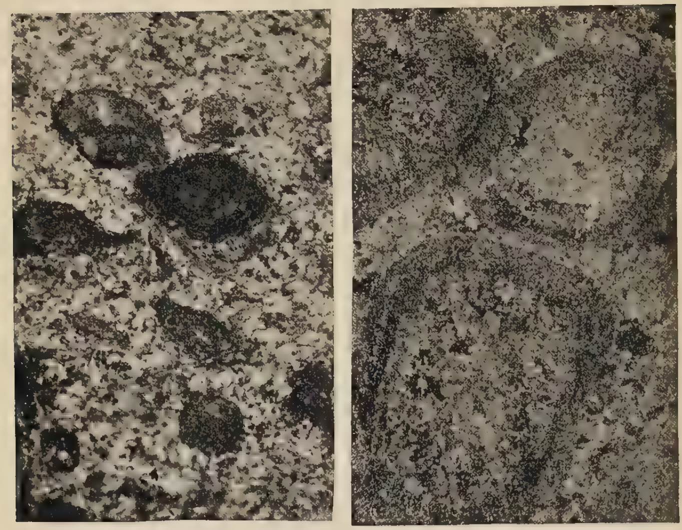
shaped masses with gentle slopes and broad valleys, such as are seen in the hills and mountains of New England and the southern Atlantic States. The views on Plate 14 are illustrative of this contrast.

Orbicular Granite. It sometimes happens that the component minerals of a granite, instead of being uniformly distributed in grains of about the same size, are collected in some spots in an unusual way and arranged in ovoid or spherical bodies. Thus in a granite from Craftsbury, Vermont, called "pudding granite," the rock is full of nodules, varying from the size of a pea to that of a nut, composed almost entirely of agglomerated leaves of black mica, as seen on Plate 15. More commonly the bodies are composed of several minerals and consist of a nucleus with a concentric outer shell or shells. The component minerals are the same as those in the main body of the rock but their proportions differ in the nucleus and in the shells, some shells consisting mostly or entirely of salic minerals, while other shells consist mostly of ferromagnesian ones. Their appearance is shown on Plate 15.

The bodies are round, ovoid, and often lenticular or spindle-shaped, as if drawn out. It was formerly thought that they represented pebbles and were a proof of the metamorphic origin of granite from conglomerates, but the arrangement and regular internal structure of the ovoids precludes such an idea and it is now generally held that they are due to some process of differentiation or aggregation of material in the magma with subsequent crystallization, though it is thought that some of them may represent inclusions of other rocks that have been melted up and recrystallized. Granites of this kind are called *orbicular* and, though not common, they have been described from Sweden, Finland, Corsica, Canada, and Rhode Island. Similar structures have also been found in diorites and gabbros.

Miarolitic Structure. The older and deeper-seated granites, and especially those that have been subjected to heavy mountain-making pressures, show little or nothing of the miarolitic structure described on page 160. The conditions have been

PLATE 15.



A. Craftsbury, Vermont. B. Kortfors, Sweden.

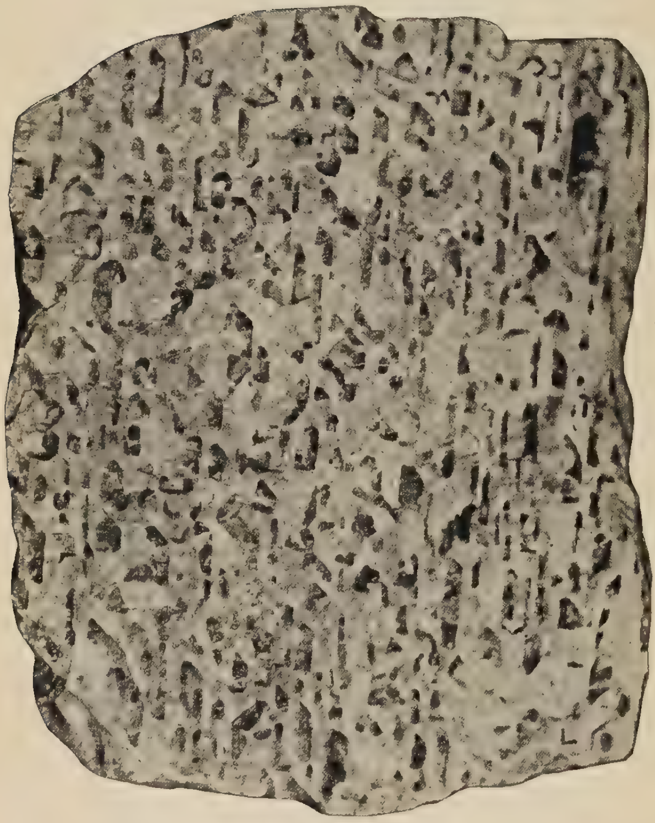
C. Stockholm, Sweden.

ORBICULAR GRANITES.

unfavorable for the formation of such cavities, or under the pressure they have been obliterated. In other occurrences and in the younger, higher or unsqueezed granites these cavities may occur, and on their drusy surfaces fine crystallizations of the minerals may be seen. The crystals from such cavities in the granite of the Pike's Peak region in Colorado, from the Mourne Mountains in Ireland, from Baveno on the Lago Maggiore in northern Italy, and from other localities, are well known in mineral collections.

Pegmatite Dikes. These are very common in granites, so much so that when the word pegmatite is used a granite pegmatite is usually understood unless the rock is otherwise specified. They have the general characters described on page 179 and the following pages. The chief minerals are *quartz* and *feldspar*, the latter being mostly *orthoclase* or the variety of it called microcline, though albite also occurs. The quartz and feldspar tend to be intergrown in such a manner that the interstices of a spongy quartz crystal are filled by an equally spongy feldspar crystal, the two sponges thus mutually filling each other's interstices and interclasping. As the quartz has no cleavage while the feldspar has, the cleavage through the intergrown mass is that of the feldspar, and upon such surfaces the quartz appears, repeating its tendency to crystal form again and again and thus producing figures which recall the script used in Arabic writings. This arrangement is called *graphic granite* and a figure of it is seen on Plate 16. It shows that these two minerals have crystallized simultaneously. The minerals also occur separately and often in huge crystals, so that such dikes are mined for commercial purposes, the quartz and feldspar being used in several technical processes such as the manufacture of china, porcelain ware, etc. The large crystals of *muscovite mica* which occur in them are the source of this material as used in stove windows, lamp chimneys, paper making, etc. In addition to these chief minerals a great variety of accessory ones are found, some of the more common of which are *tourmaline*, *garnet*, *beryl*, and *spodumene* among

PLATE 16.



GRAPHIC GRANITE.

the silicates, *apatite*, *triphylite*, and a series of related phosphates, and a variety of kinds containing rare earths. Some of these minerals, like the colored tourmalines, topaz, beryl, etc., are valuable because they afford material suitable for cutting into gems; others are useful as sources of the rarer elements used in chemical and some technical processes, such as the making of Welsbach mantles. Uraninite, which is restricted in its occurrence to pegmatites, is a principal source of the world's radium. A full list of all the minerals known to occur in these pegmatites would include a large proportion of all the kinds known in mineralogical science.

Inclusions. Schlieren. It is not uncommon to find in granite the various kinds of inclusions described on pages 163 and 164. Sometimes the composition and form of these show that they are fragments of previously existing rock formations broken off and engulfed in the granite magma. These are most common near the border of the mass. They may vary in size from an inch across, or less, to masses a number of yards long. When they occur in the center of the mass, it may be suspected that the granite has not been deeply eroded below the former overlying roof of other rocks.

Some of the apparent inclusions are the *schlieren* described. They may consist wholly of quartz and feldspar, or nearly so, and thus be very light in color, or they may be extremely rich in biotite or hornblende or both, with iron ore, and thus very dark in color. Such dark streaks may at times be due to melted-up inclusions but they may also be caused by aggregations of the normal dark minerals of the granite and in general are ascribed to processes of differentiation.

Complementary Dikes. Very frequently it will be found that bodies of granite are cut by complementary dikes as described on page 172. The *leucocratic* dikes are commonly composed almost solely of quartz and feldspar with which is usually associated a little white mica. The rock has a finely granular, sugar-textured appearance. This variety of granite is called *aplite*. Sometimes small black specks of biotite or hornblende or of black tourmaline may be seen in it, but always the dark minerals play a very subordinate rôle. The color of the aplites is nearly constantly very light, white, flesh-color, pale yellow, gray, or brown being common. Sometimes these rocks are so fine of grain that they pass into felsites of the colors mentioned, and sometimes they are porphyritic with phenocrysts of quartz or feldspar or both and are thus granite or felsite porphyries. But most commonly they are even-granular with a grain about like that of loaf sugar and they characteristically occur as dikes. They are mostly noticed cutting the granite mass, less commonly the surrounding rocks. They are of all sizes, from a fraction of an inch to a number of yards in breadth. If the larger ones are traced along the outcrop it may sometimes be found that they change into pegmatite dikes.

The *melanocratic* dikes, sheets, etc., complementary to the quartzo-feldspathic aplites described above, are dark to black heavy rocks of basaltic aspect. They are composed chiefly of biotite-mica, hornblende, pyroxene, and magnetite with feldspars, but very commonly the grain is too fine for these minerals to be distinguished and they are likely to be classed as basalts. Many of them, however, when biotite is the prominent ingredient, have a characteristic glimmering appearance, or the plates of biotite may be distinctly seen, and they are then known as *mica traps.* The most characteristic color of these rocks is a dark stone gray. Occasionally porphyritic crystals of hornblende or of feldspar, as well as of biotite, appear in them, and not uncommonly fragments of the granite which they cut and of other rocks. They alter and weather down into soft greenish material or into brown earthy masses. The earlier stages of alteration by the elements are marked by the formation of carbonates, and such altered rocks effervesce freely when treated with acid.

They occur characteristically in dikes, usually of but a few feet in width, but, as previously mentioned, also in intrusive sheets, small laccoliths, etc. While they often cut the granite they are more likely to be found in the outer zone of rocks surrounding it, and sporadic occurrences may be discovered a number of miles distant from the parent mass. The origin of these complementary dikes has been already discussed on pages 181 to 184.

Contact Phenomena. It is especially around great granite intrusions that the contact phenomena described on page 184 are seen in their greatest development and perfection. In the endomorphic modification the granite may become a felsite or granite porphyry at the contact, or it may show a differentiated border zone (see page 170) and become so enriched in the dark silicates as to pass into a diorite or dolerite border facies, or, more rarely, on the other hand, may be so poor in these as to present a marginal facies of aplite, quite like that seen in the complementary dikes. The first cases mentioned are purely textural modifications; the second are chemical and mineralogical. More rarely, granites have a border of pegmatite. With respect to exomorphism, the changes described in the previous chapter are more frequently seen and have been more extensively studied in connection with granites than with any other variety of igneous rock, on account of the common occurrence of the granites. Around the great granite batholiths these effects are often profound and far reaching, involving tracts as much as several miles in width. Such areas are often of great interest and importance, not only from the geological standpoint, but because they are frequently the site of important ore deposits. If granite comes directly against sedimentary rocks with vertical contact and the latter show no evidence of metamorphism, it may be safely assumed that faulting or dislocation has brought them together.

Weathering of Granite into Soil. Through the action of the atmosphere, of water, of heat and cold, granite breaks down into soil. In northern and in temperate regions, such as eastern North America, as Merrill has shown, this change is at first largely a mechanical disintegration and the resultant material differs in its general chemical composition but slightly from the original rock.

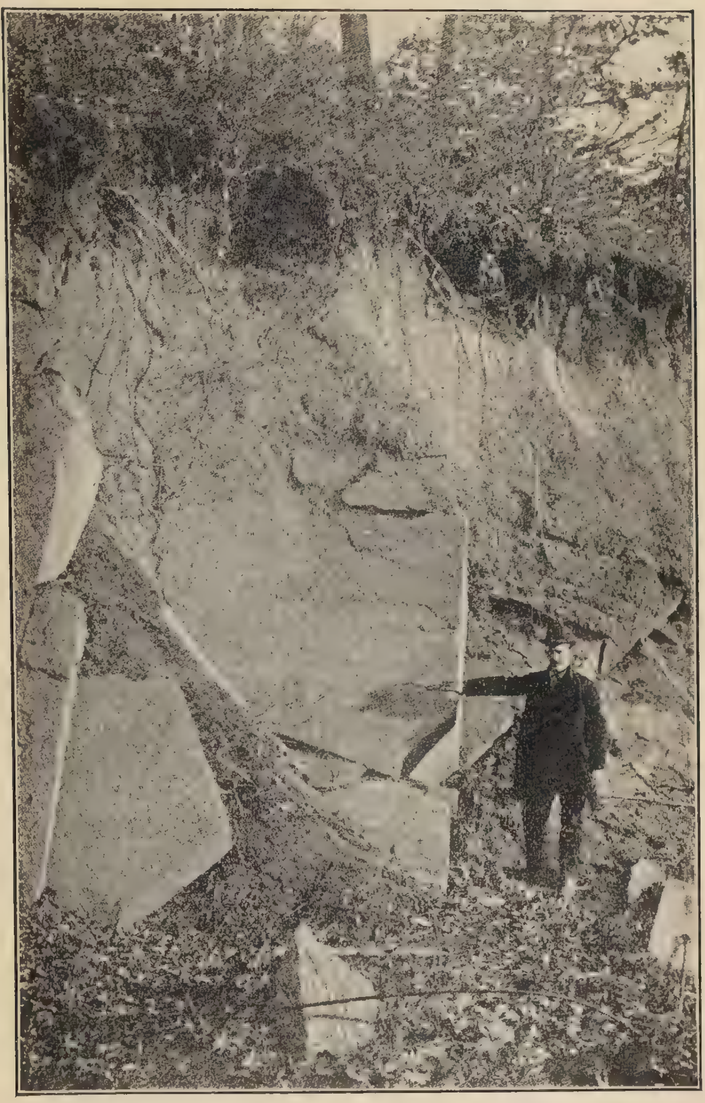
In appearance, however, granite may alter considerably as it changes. The biotite tends to bleach and lighten, and ferrous compounds tend to become ferric and the iron oxide to leach out, staining the rock red to dark brown. At the same time the granite loses its firm texture and becomes more or less friable and crumbly. Finally it falls into an angular gravel or sand, composed mainly of particles of quartz and feldspar, called *gruss*. See Plate 17.

From this stage, as the change into soil becomes more complete, the most important process is the conversion of the feldspar into kaolin, according to the following reaction.

$$\overset{\text{Orthoclase}}{2\,KAlSi_3O_8} + \overset{\text{Water}}{2\,H_2O} + \overset{\text{Carb. diox.}}{CO_2} = \overset{\text{Kaolin}}{H_4Al_2Si_2O_9} + \overset{\text{Quartz}}{4\,SiO_2} + \overset{\text{Potas. Carb.}}{K_2CO_3}$$

This reaction begins as soon as the rock is exposed; it has only partially taken place when the rock crumbles, but after that goes on slowly but steadily until the feldspar is eventually wholly changed into clay. As a result, a soil consisting of a mixture of clay and quartz sand, stained reddish or yellowish by the iron compounds, is formed. Such a soil is called a *loam.* Usually the process is not entirely complete and the soil contains more or less feldspar in small particles, undergoing alteration. This has an important bearing on the self-renewal of its fertility.

The soil-forming process is one of the most important that takes place in the great laboratory of Nature, for by means of it, not only is the solid rock converted into soil, but one of the most essential of plant foods, the potash, is converted into soluble form in which it can be assimilated. At the same time the other essentials of plant food, the silica, magnesia, lime, etc., are also unlocked from the rocks and rendered available. Thus by their aid plant life is able to grow and produce from water, carbon dioxide, etc., those substances upon which all animal life ultimately depends.



GNEISSIC GRANITE, THROUGH WEATHERING, PASSING FROM FIRM ROCK BELOW INTO ALTERED ROCK AND SOIL ABOVE.

(Merrill, Bulletin Geological Society of America.)

In certain tropical regions characterized by marked seasonal distribution of rainfall, the decay of granite gives rise to a red or yellow-brown ferruginous earth to which the name of *laterite* is given. It has been shown to consist of a mixture of quartz sand with hydrargillite, a clay-like substance with the composition $Al(OH)_3$, colored by iron hydrates. The name was originally applied in India to soils formed from the basalts of the great Deccan plateaus mentioned later.

In warm and tropical deserts the surface of granites is coated with a brownish or black skin, sometimes with a luster like varnish, appropriately called desert varnish, due to the alteration of the iron-bearing components and the formation of iron and manganese compounds. This coating also occurs on other kinds of rocks.

Occurrence of Granites. Granite is one of the most common and widely occurring of igneous rocks, and plays a prominent rôle in the formation of the continental masses. In the form of stocks and immense batholiths it makes the central core of many of the great mountain ranges and is revealed by later erosion. In those parts of the Earth's surface that have been subjected to repeated disturbances of the crust and profound erosion, granites are common rocks. Thus great masses of different ages of intrusion are found in eastern Canada, in New England, and generally along the region of the Piedmont plateau from southern New York into Georgia. They occur again in Missouri, Wisconsin, etc., in isolated areas; but in general, until the Rocky Mountains region is approached, the Central States, which compose the Mississippi Valley, being covered with stratified rocks, are devoid of them, though it has been shown in recent years, as a result of drilling for oil, that they form a large part of the basement on which these later rocks lie. In the Rocky Mountains and in the far western States they are of great importance. Likewise in Europe, in western and southern England, in Ireland, in Scotland, in various places in France and Germany, and in the Alps they are of common occurrence and their exposures form considerable areas. Such a list of occurrences might be almost indefinitely extended but enough has been said to show the importance and wide distribution of granite.

Syenite

Composition. Syenites are granular rocks composed chiefly of orthoclase. They differ from granites in that they contain no quartz or only a negligible quantity. They may consist entirely of feldspar, but usually more or less hornblende, biotite, or pyroxene is present. These, however, are subordinate in amount to the feldspar. If the rock is fairly coarse-grained, occasional particles of magnetite and other minerals may be seen, but these are only accessory and not of the importance of the ones mentioned. Occasional minerals which produce varieties will be mentioned presently.

According to the predominant kind of ferromagnesian mineral, the rock is spoken of as hornblende syenite, biotite syenite, or augite syenite. All of these are here treated under the general heading of syenite; but in one variety the rock may have a particular mineral composition that makes it of especial interest and therefore deserving of separate description. Generally this variety may be identified by observing with care the special features which it presents and which are described in one of the paragraphs that follow, otherwise it cannot be distinguished and must be classed in the general group of syenites. In this variety the rock contains in addition to the feldspars and other minerals a notable amount of nephelite or this and its congener, sodalite. We may then divide the group of syenites as follows:

a. *Syenite*, in general consisting chiefly of orthoclase, without quartz.

b. *Nephelite Syenite*, consisting chiefly of alkalic feldspars with nephelite.

Properties of Syenite. The *texture* of syenites is usually even granular, but sometimes the feldspar shows a tendency to assume a flattened tabular form like that of a book; its cross sections on the rock surface are then elongated and often arranged more or less parallel, an arrangement which is thought to be due to movements of the fluid mass during crystallization. Porphyritic varieties also occur as in granite, and these grade into syenite porphyry. The *color* is variable like that of granites; white to pink or red, or gray or yellow tones are common, gray especially so. The *specific gravity* varies with the minerals and their proportions; it may extend from 2.6 to 2.8. In a tendency to *miarolitic structure*, in *jointing*, in erosion forms, in *alteration* into soil, in *inclusions*, and in *contact metamorphism*, etc., what has been said in regard to granite applies also to syenites and need not be repeated. They are also accompanied by pegmatite dikes, but these are not so common as the granite pegmatites.. The syenite pegmatites also yield a great variety of minerals.

Chemical Composition. Chemically, the syenites are distinguished from the granites by a lesser amount of silica, which accounts for the absence of the quartz; in other respects they resemble them. These characters may be seen in the following table of analyses.

ANALYSES OF SYENITES

	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	H_2O	XyO	Total
I	60.7	19.6	1.5	3.0	0.8	2.3	4.9	5.9	0.3	0.6	99.6
II	60.2	20.4	1.7	1.9	1.0	2.0	6.3	6.1	0.3	0.4	100.3
III	61.6	15.1	2.0	2.2	3.7	4.6	4.3	4.5	0.7	1.0	99.7
IV	62.5	16.5	2.4	2.0	1.9	4.2	4.4	4.6	0.6	1.3	100.4

I, Belknap Mountains, New Hampshire; II, Fourche Mountain, Arkansas; III, Little Belt Mountains, Montana; IV, Plauen near Dresden, Germany. XyO = Small amounts of other oxides.

Occurrence of Syenites. Syenites are not very common rocks, and, while they sometimes occur in independent masses, they are very likely to be connected with larger bodies of granite, which by the diminishing of quartz passes into syenite. In the United States they occur in several places in New England, at Mount Ascutney, in the White Mountains and adjacent region, on the coast north of Boston, also in Arkansas, in Montana, and in a number of other localities. They are found in several places in Germany and in the Alps. An important area of them exists in south Norway. In comparison with the great batholiths and stocks of granite distributed so generally in the continental masses, they are, geologically speaking, of relatively small importance.

Uses of Syenite. For all constructional and other commercial uses syenite has the same value as granite. On account of its relative rarity, compared with the latter rock, it is, however, little used. Its crushing strength is equal to that of granite, and from experiments by J. F. Williams on syenite from Arkansas it may be even greater. Its weight per cubic foot is about the same. The absence of the quartz, which is harder than feldspar, should make it an easier stone to dress and polish, and practically it resists weathering as well, if not better. The absence of the quartz makes it also a better stone in resisting the heat of fires (compare granite, page 212) and it would be in consequence a more advantageous material for building in our large cities. If these advantages over granite were more generally understood it is probable that the accessible occurrences in New England would be more extensively exploited. The beautiful dark gray syenite of south Norway, with pearly blue reflections, is considerably used in northern Europe as an ornamental stone.

Nephelite Syenite. This variety is distinguished by the fact that in addition to the feldspars, which are almost wholly alkalic in composition, a considerable amount of nephelite is present. This mineral is sometimes flesh-colored but usually it is smoky gray. In its lack of good cleavage it resembles quartz, but it can be readily distinguished from the latter by the gelatinization test (page 112). It is generally present in formless grains mixed with the feldspars, but sometimes shows the outlines of a crystal form. It is likely to be accompanied by sodalite, which is often of a bright blue color, in grains or, if the rock is very coarse-grained, in lumps and masses; if it is thus present it is useful in aiding to distinguish this rock from common syenite. Nosean and cancrinite may also be present. Mica (lepidomelane), hornblende (arfvedsonite), and pyroxene (ægirite) are usually present in variable amounts, in plates, grains, or prisms, of a black color, and containing considerable sodium and iron. The presence of sodium in the minerals of this rock is readily understood from a consideration of the chemical analyses, given below, which show the composition of the magma from which they crystallized.

The *color* of nephelite syenites is variable but is commonly gray. The *texture* is granular, sometimes rather porphyritic. The book-shape of the feldspars mentioned above is common. The rock is likely to contain many accessory minerals but usually only in microscopic sizes; some of these are of especial interest on account of the rare earths they contain. It is also prone to exhibit in places great variations of the constituent minerals, giving rise to different facies. Many of these varieties have received special names. Usually it is cut by *complementary dikes*, and these are of a different character from those found associated with granites and common syenites; one is a pale brown or pink felsite, another a bright to dark green rock called *tinguaite* which owes its color to microscopic needles of ægirite. The tinguaite usually contains nephelite and gelatinizes with acid. The lamprophyres complementary to these are heavy dark rocks of basaltic aspect often showing distinct to large phenocrysts of biotite, augite, or hornblende; they are particular varieties of melaphyre (camptonite).

The chemical composition of nephelite syenites is illustrated in the two analyses that follow:

	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	H_2O	XyO	Total
I	58.8	22.5	1.5	1.0	0.2	0.7	9.6	4.9	1.0	0.3	100.5
II	53.1	21.2	1.9	2.0	0.3	3.3	6.9	8.4	1.4	2.0	100.5

I, Salem Neck, Mass.; II, Magnet Cove, Arkansas. XyO, small quantities of various oxides.

It will be seen that the most striking thing in these magmas is the high amount of alumina and alkalies, with moderate silica. It is this which causes the formation of nephelite ($Na_2O \cdot Al_2O_3 \cdot 2\ SiO_2$) rather than albite ($Na_2O \cdot Al_2O_3 \cdot 6\ SiO_2$), there being not enough silica to convert all the alumina and alkalies into feldspar. From this it may be seen that free quartz and nephelite cannot crystallize from the same magma; the silica would convert the nephelite into albite, and therefore these two minerals are not found in the same rock. Sometimes nosean is present; cancrinite may also occur, and of the associated minerals zircon is perhaps the most characteristic. In this connection the description of the feldspathoid group in the part dealing with minerals should be read.

Pegmatite dikes occur in connection with nephelite syenites, and those of south Norway and Greenland are especially interesting for the great variety of minerals, many of them composed in part of the rarer elements, which they have afforded.

Nephelite syenites usually occur in rather small stocks or large dikes; relatively large areas of them are known in only a few places, Greenland, south Norway, and Lapland. They are of rare occurrence and geologically are of small importance compared with granites, gabbros, and diorites. In the United States they are found at Litchfield, Maine; Red Hill, New Hampshire; Salem, Massachusetts; Beemerville, New Jersey; Magnet Cove, Arkansas; Cripple Creek, Colorado; in western Texas and a few other localities. In Canada they occur at Montreal; Dungannon, Ontario; Ice River, British Columbia. Noted localities for these rocks and their associated minerals in Europe are in south Norway; Alnö Island, Sweden; Kola Peninsula and Miask, Ural Mountains, Russia; Foya, Portugal; and Ditrö, Transylvania. The rock is too uncommon to be of commercial importance but makes an excellent building stone where it occurs. That in the neighborhood of Magnet Cove, Arkansas, has been thus used.

Corundum Syenite. In all the different varieties of syenite described above, instances have been found in which the rock contains, in addition to the usual constituents, a notable amount of corundum. The appearance of this mineral is due to the fact that the magma contains more alumina than the alkalies and lime present can turn into feldspars and feldspathoids, and this excess is forced to crystallize out as corundum (Al_2O_3), just as in granites the excess of silica is compelled to form quartz (SiO_2). The mineral occurs in crystals, either hexagonal prisms or barrel-shaped, or in grains and lumps, and is usually of a gray color. It is easily identified by its excessive hardness.

Such occurrences have been found in central Montana in common syenite; in syenite and nephelite syenite in Renfrew, Hastings, and other counties of Ontario, Canada, where these rocks have been traced in a belt a distance of over a hundred miles; and in a similar manner in the Ural Mountains and in Coimbatore district, India. Some of these occurrences, notably the ones in Canada, are of economic value as a source of this valuable abrasive. Corundum also occurs in other kinds of igneous rocks as mentioned under dunite.

Diorite

Composition. The diorites are granular igneous rocks composed of plagioclase feldspar and one or more ferromagnesian minerals, in which the amount of the plagioclase equals or exceeds the amount of the dark minerals. The dark minerals may be biotite, hornblende, or pyroxene and they may occur either singly or together. The hornblende is usually black, sometimes dark green, and, while often in bladed or prismatic forms, it is also often in short thick crystals or grains. It is at best difficult, and generally impossible, to distinguish the pyroxene from the hornblende. While any kind of plagioclase may be present, in the great majority of cases, as learned from microscopical studies, it is generally a moderately calcic variety. This latter determination cannot be made on the hand specimens, because the composition of the plagioclase feldspars cannot be determined megascopically. It is not uncommon for some quartz to be present and this can generally be identified with the lens; if it is present in notable quantity the rock is called quartz diorite.

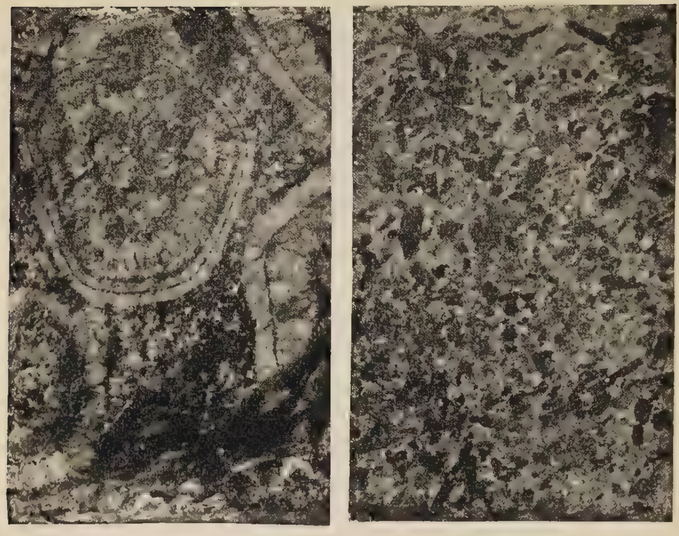
While the rocks determined as diorites by this megascopic classification will correspond in a general way with the greater part of the diorites of the more strict classifications founded on microscopic and chemical methods, they also include some gabbros and less common rocks which, for one reason or another, have been given various names by petrographers.

General Properties. The *color* of diorites is gray to dark-gray ~~or greenish~~. It is determined by the proportion of dark minerals to feldspar. The different varieties of diorite are due to the color, coarseness of grain, etc. The *texture* of the rock is granular (granitic). The porphyritic texture, while not unknown, is far less common than in granite. Sometimes the black hornblende prisms are distinct enough to produce an impression of porphyritic texture which is dispelled as soon as one compares the average size of the crystal grains. Orbicular structures are known to occur. A rock from Corsica exhibiting such structure has been used somewhat as an ornamental stone; it is illustrated on Plate 18. Miarolitic cavities occur as in granite; they are often masked by being filled with calcite. Pegmatite dikes also occur and the minerals are somewhat different from those in the granites. Fluidal or somewhat parallel arrangements of the component minerals are not uncommonly seen, and these produce tendencies to gneissic structure. Diorites are also frequently cut by complementary dikes, of much the same general appearance as those in granites, or these are found in their immediate neighborhood in dikes and sheets. Thus they may be traversed by light-colored aplites and by dark, heavy traps.

Their jointing is like that described for granites.

Chemical Composition. This varies considerably with the relative amounts of feldspar and dark minerals and with the particular varieties of these that are present, and is also somewhat influenced by the accessory minerals that may occur. The following table illustrates this and shows also how the increase of lime, iron, and magnesia over the proportions of these oxides in granites and syenites causes the increase in the amount of hornblende and pyroxene.

PLATE 18.



A. ORBICULAR DIORITE, CORSICA.

B. DIORITE.

C. DIORITE, COMMON TYPE.

ANALYSES OF DIORITES

	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	H_2O	XyO	Total
I	55.1	20.2	1.5	4.3	1.8	7.0	4.3	2.8	1.1	1.7	99.8
II	58.0	18.0	2.5	4.6	3.6	6.2	3.6	2.1	0.9	1.2	100.7
III	47.1	18.1	3.0	8.5	7.3	6.6	2.4	2.8	3.6	0.5	99.9
IV	43.9	16.2	4.0	10.1	5.1	9.6	2.9	1.5	1.6	4.9	99.8

I, Diorite, Little Belt Mountains, Montana; II, Electric Peak, Yellowstone Park; III, Malvern Hills, England; IV, Belknap Mountains, New Hampshire. XyO = Small quantities of various oxides, TiO_2, MnO, etc.

Occurrence, Uses, Etc. While diorites are found in many places as independent intrusions, they are also very likely to be, on the one hand, connected with granites, on the other with gabbros, and usually these pass into each other. They do not form such vast batholiths or stocks as the granites or the gabbros, and, especially as independent masses, are more likely to be found as small stocks, large dikes, etc. They have a very wide distribution and are found in all parts of the world where the deeply-seated igneous rocks have been laid bare by long erosion. What has been said of granites in this respect would be largely true of diorite. Owing to its dark color, diorite is not so extensively used for architectural purposes as granite, though, so far as strength, durability, and capacity for receiving a high polish are concerned, it would furnish excellent material in many places. It is somewhat heavier than granite, its specific gravity ranging from 2.8 to 3.1; at 3.0 a cubic foot of it would weigh about 187 pounds.

Gabbro

Composition. The gabbros are granular igneous rocks consisting chiefly of ferromagnesian mineral and plagioclase, in which the amount of ferromagnesian mineral equals or exceeds that of the plagioclase. The distinction between gabbro and diorite is based on the relative proportions of ferromagnesian mineral and plagioclase: in gabbro the ferromagnesian content predominates, in diorite it is subordinate. There are of course many rocks in which the ferromagnesian minerals and the plagioclase are roughly equal in amount and such intermediate rocks may with equal propriety be classified as either diorite or gabbro. The ferromagnesian minerals may be pyroxene, hornblende, or olivine, and they may occur either singly or together. The olivine can sometimes be detected with the lens as yellowish or green grains. Careful inspection will often show occasional bronzy flakes of biotite, but this mineral is distinctly rare in gabbro as contrasted with diorite. The pyroxene is usually dark greenish when examined with the lens, often black to the eye alone, and sometimes it is of the variety diallage, which has a pronounced apparent cleavage in one direction, and is of a gray-green color and often almost micaceous appearance, at times somewhat brassy or semi-metallic in luster. A test with the knife point for cleavage shows at once its non-micaceous character. The feldspar in gabbros is a soda-lime variety, generally labradorite; its twinning striations on cleavage surfaces can generally be seen, but its composition cannot be determined megascopically. It is usually in formless masses or grains like the other minerals, but not infrequently it has a tabular or book-like form and the sections on the rock face have an elongated shape, the striations running parallel with the elongation. Sometimes the feldspar is fresh and glassy; the two feldspar cleavages are then good and the striations if visible are distinct; sometimes the feldspar is waxy in appearance, of a glimmering luster to dull, often with a bluish tone; here the cleavage is poor or even apparently wanting and striations cannot be seen. In the last type the feldspar is more or less affected by alteration to other minerals as described on page 42.

A distinction is made by petrographers by which gabbros are divided into two groups, depending on the variety of pyroxene present. If this is the monoclinic, calcium-bearing augite or diallage, the rock is called gabbro; if it is the orthorhombic hypersthene, which is without calcium, the rock is called *norite*. This distinction cannot be made in megascopic determinations unless some of the pyroxene is extracted from the rock and tested chemically or optically, hence the norites are here included under gabbro. Norite is a rock of great economic interest, for at many localities, notably at Sudbury, Ontario, immense bodies of nickeliferous pyrrhotite ore are inclosed in it. A rarer variety of gabbro consists of plagioclase and olivine without pyroxene and is called *troctolite*. Some rare rocks with alkalic feldspar which are variously classified and named by petrographers are also here included under gabbro.

General Properties. The *color* of gabbros is usually dark, dark gray, or greenish to black; very rarely reddish. In some varieties in which diallage is the kind of pyroxene present and the grain is moderately coarse, the rock is much lighter in tone and of a medium gray or greenish-gray. The same is true in many rocks that are more or less altered; compare with what is said of the feldspars above. The *texture* is granitoid or granular, sometimes with a porphyritic tendency from the elongation of the feldspars, but true porphyritic texture is very rare. Miarolitic cavities are much less frequent than in granite and syenite. Orbicular gabbro has been found in California. A fluidal or banded structure, which is produced by drawn-out layers of varying composition and which simulates a gneissic structure, has been described from several localities, from the Hebrides, California, and Minnesota. *Pegmatites* are also occasionally found in gabbros; they consist of the usual minerals of the rock, but are richer in feldspar than the gabbro with which they are associated. In south Norway the pneumatolytic processes attending the intrusion of gabbros have formed much scapolite and other minerals in the gabbro at its border and in dikes in the contact zone; of these minerals apatite is the most prominent and occurs sometimes in large masses. Complementary dikes, etc., occur in gabbro masses but are not so notable a feature as in the foregoing groups. In this connection what is said concerning peridotites may be consulted.

ANALYSES OF GABBRO

	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	H_2O	XyO	Total
I	47.9	18.9	1.4	10.5	7.1	8.4	2.7	0.8	0.6	1.7	100.0
II	48.9	8.8	1.0	9.5	15.2	14.7	0.6	0.1	0.6	0.7	100.1
III	49.9	18.5	2.1	8.4	5.8	9.7	2.6	0.7	1.0	1.4	100.1
IV	52.8	17.8	1.2	4.8	4.8	12.9	3.0	0.5	1.2	0.5	99.5
V	40.2	9.5	9.7	12.2	8.0	13.1	0.8	0.2	0.5	5.5	99.7

I, Adirondacks, New York State; II, Orange Grove, Maryland; III, Pigeon Point, Minnesota; IV, Band rich in feldspar, poor in pyroxene, Isle of Skye, Hebrides. V, Band rich in pyroxene, poor in feldspar, Isle of Skye. XyO = small quantities of various oxides, chiefly TiO_2.

Chemical Composition. The gabbros, as a rule, contain larger amounts of lime, iron, and magnesia, and less of silica and alkalies than any of the previously described rocks, as may be seen from the table annexed.

Analyses IV and V show how the chemical composition of the banded gabbros varies in the different streaks with corresponding variation in mineral contents.

Occurrence. Gabbros are widely distributed and common rocks. They occur as laccoliths, stocks, and batholiths and in dikes, similarly to granite. They are also found as stocks and necks of old volcanoes cutting the stratified beds of the younger mountain regions. In these they may also be found as thick intrusive sheets. Gabbros have been held to occur also as the central portion of thick extrusive sheets, as in the Hebrides, in Sweden, and in the Lake Superior region. If this is true, it is due to the low viscosity of the magma, its liquidity, and ready crystallization.

In the United States, gabbros are found in many places in New England, as in the White Mountains. They are found in the Adirondacks and at Cortlandt on the Hudson River in New York State, in Maryland, etc.

They occur in the Lake Superior region and elsewhere in Minnesota and in various places in the Rocky Mountains and in California. They are extensively distributed in Europe, in southern England, in northern Scotland, especially on the islands of the Hebrides, in Norway and Sweden, and in Germany. They are in fact almost as widely distributed as granites, but they do not form, as a rule, such large masses.

Alteration of Gabbro. It is common to find that where gabbro massives occur in the older rock complexes and in folded mountain ranges, they are surrounded by a mantle of hornblende schist into which the gabbro gradually passes by transitional phases. This mantle is caused by the pressure, shearing, and other metamorphic agencies brought about by the orogenic processes, as mentioned under metamorphism, hornblende, etc. The processes have acted upon the pyroxene of the gabbro, converting it into hornblende and producing the schistose structure. It may happen through pressure and shearing that a schistose or, perhaps better, a gneissic structure is induced in the gabbro without change of the pyroxene to hornblende, and we should then have a gabbro-gneiss or gabbro-schist, but generally the change to hornblende occurs. If olivine is present it also is altered to amphibole. Very often garnet appears as a new mineral resulting from the process. While the change to hornblende is usually accompanied by the assumption of a more or less pronounced gneissic or schistose structure, this is not always the case; the rock sometimes retains a massive granular character. In another mode of alteration of gabbros the feldspar is changed into a substance called saussurite, which was formerly thought to be a distinct mineral, but which the microscope has shown to be a mixture of albite and zoisite. The feldspar, or rather that which replaces it, has no cleavage and is waxy-looking. The pyroxene is changed to hornblende, which tends to have a bright to grass-green color and is the variety called smaragdite. Other minerals are also formed, but megascopically the waxy-looking saussurite and green hornblende predominate. This change may take place without formation of schistose structure and it seems probable that this alteration is due more to the chemical and less to the dynamic agencies of metamorphism. Such rocks have been called saussurite gabbro.

In the process of weathering through the agencies of the atmosphere, gabbros give rise to clay soils deeply colored by the oxides of iron and mingled with fragments of still undecomposed minerals.

Iron and Other Ore Deposits. There are frequently found in large gabbro intrusions masses of iron ore, sometimes consisting of magnetite, but generally of ilmenite or mixtures of the two. Usually these are more or less mingled with the minerals of the gabbro itself, especially pyroxene and olivine. The character of the occurrences and the manner in which they gradually shade into the normal gabbro show that they are only a facies of the gabbro in which the iron ore, usually scattered through it in small grains, is here locally concentrated in great abundance. Such ore deposits are sometimes found at the border of the intrusion, though often scattered in masses through it or at the center. They are known in many places, in the Adirondacks, in northern Minnesota, in Canada, Norway, Sweden, and elsewhere. If titaniferous iron ores could be successfully smelted, many of the deposits would undoubtedly be of great value.

Sulphide ores have segregated in some gabbro rocks in a similar manner. This is especially true of the sulphide of iron called pyrrhotite, which is often nickel-bearing and hence of great value as a source of this useful metal. In some places these deposits are accompanied by valuable amounts of copper in the form of chalcopyrite, copper-iron pyrites, and it has been remarked that as the percentage of copper rises that of nickel falls. Such deposits in gabbros, or in rocks derived from them, have been worked in Norway, in Lancaster County, Penn., and especially at Sudbury, Ontario. As already mentioned, it is with the norite variety of gabbro that the nickeliferous pyrrhotite ore bodies are chiefly associated.

The origin of this kind of ore deposit in an igneous rock has been described on page 175.

Use of Gabbro. The gabbros are well suited for constructional work and architecture, but as a rule have not been extensively used, probably very largely on account of their dark color. In Sweden they have received considerable attention for monumental and other uses. In the United States they have been used for building in the Lake Superior region, as at Duluth, and quarries of them at Keeseville in the Adirondacks and in Vergennes, Vermont, have been worked. They take a high polish, are sufficiently durable, and are much easier to work than granite.

Anorthosite. This rock is composed wholly, or nearly so, of a plagioclase feldspar, usually the variety labradorite. Sometimes small quantities of a ferromagnesian mineral, pyroxene, are sprinkled through it in grains and specks, or small masses of magnetite or ilmenite can be seen. This simple mineral composition makes it resemble, in the hand specimen, especially when the grain is rather fine and the colors light, both marble and quartzite, also rocks consisting of a single mineral. From the former it is easily told by its superior hardness, since the feldspar cannot be scratched by the knife, while marble is easily cut or scratched; and from the latter by the cleavage of the crystal grains which can usually be easily seen with a lens. While these characters help to distinguish the rock, its identification can be made certain only by determining the kind of feldspar present. This can be done in the field only when the cleavage surfaces of the feldspars are sufficiently large to permit one to see on them the characteristic twinning striations of plagioclase (see page 36). In the laboratory the feldspar can be identified by blowpipe and chemical tests, or more readily and precisely by optical tests.

The rock is normally white and sometimes shows this color, but generally it is colored yellowish to brown, or, more commonly, some shade of gray, light gray, blue or smoky to dark gray and almost black. The very dark exotic color is due to an included pigment, perhaps ilmenite dust, but it is notable that where these rocks have been subjected to orogenic pressure and especially when they have been sheared and granulated and have assumed gneissic structure, the dark color tends to disappear and they become lighter. The chemical composition of anorthosite is practically that of a labradorite feldspar (Anal. IV, page 41).

Mineralogically, the anorthosites are related to the gabbros, for they contain the same kind of feldspar and often, as stated above, there is more or less pyroxene; if this latter increases in amount, passages into gabbro may occur; and in masses of gabbro, facies that are poor in pyroxene and thus transitional to anorthosite occur. Geologically, however, they occur quite independently of gabbros. They are not common rocks, so far as the number of occurrences is concerned, but are of importance from the vast masses that some of them form, notably in Canada and Norway. They are found in Canada in separate areas from the west coast of Newfoundland and the east coast of Labrador down through Quebec into eastern Ontario. One of these areas, drained by the Saguenay River, covers nearly 6000 square miles, while one near Montreal comprises about 1000 square miles.

Another region is in the Adirondack Mountains in northern New York State, where there are 1200 square miles composed of this rock. Small occurrences of a nearly related type are found also in the White Mountains, New Hampshire. Anorthosite is found again in considerable masses in Minnesota on the Lake Superior coast.

In Europe, anorthosite occurs in Norway in large areas on the west coast at Bergen, at Ekersund; and on the Sognfiord. It is also found in Volhynia in Russia.

Anorthosite is the most abundant representative of the group of monomineral rocks, i.e., igneous rocks that are composed essentially of *one* mineral. It is regarded as having been formed by magmatic differentiation from a gabbro magma, whereby the labradorite crystals as they separate from the magma, being heavier than the magma, sink to the floor of the chamber and accumulate there. It is probable that the labradorite crystals are remelted and so form an anorthosite magma.

The labradorite of this rock sometimes shows a beautiful opalescent play of colors, especially a deep blue. Cleavage pieces from the coarse and massive rock of the coast of Labrador have long been known and cut as ornamental stones. Similar material comes from near Zitomir in Volhynia.

Dolerite

Definition and Minerals. The dolerites comprise those varieties of diorite and gabbro that, on account of increasing fineness of grain, cannot be safely determined or distinguished from the coarse-grained basalts.

This term as here used comprises not only the finer-grained diorites and gabbros but also much of what is termed "diabase" by the petrographers, as well as occasional rare rocks which need no mention here.

The feldspar, which is seen in larger or smaller grains and sometimes in more or less extended lath-shaped sections, is known from microscopic studies to be chiefly a soda-lime variety. The ferromagnesian minerals are in dark grains, perhaps short columnar; their cleavage surfaces can usually be seen but it cannot be said whether they are hornblende or pyroxene or a mixture of both. Sometimes olivine is also present, and if the yellow-green grains of this mineral can be detected it is very probable that pyroxene, and not hornblende, is the chief ferromagnesian mineral. In addition the lens will often show bronzy-looking flakes of biotite and metallic steel-like specks of iron oxide (magnetite or ilmenite) or sometimes brass-like crystals or grains of pyrite.

Color. Owing to the equal or predominant amount of ferromagnesian minerals, the color of these rocks is dark, medium or dark gray, or greenish to black. As in most rocks, the tone of color is best observed in viewing the rock at a little distance, so that the individual grains become indistinguishable and only their mass effect is seen.

General Properties. The *texture* of these rocks is granular to fine granular; they are sometimes porphyritic, as described in the following section on the porphyries. Their *chemical composition* is in general similar to that of the diorites and gabbros already given and need not be repeated. They are heavy, the *specific gravity* being from 3.0 to 3.3. Their *jointing* is usually small cuboidal, wedge-shaped or platy, often columnar and sometimes on a very large scale, though generally this structure is not so perfect as in the finer-grained basalts. It is most likely to occur in dikes, very thick intrusive sheets, and massive extrusive flows.

Occurrence. The dolerites do not occur in large stocks and batholiths like the diorites and gabbros, though not infrequently these latter rocks pass at the margin of the intrusion into an endomorphic facies consisting of dolerite. As intrusives they belong in the minor class, being found in dikes, small laccoliths, and intrusive sheets, the last often of great thickness, and in thick massive lava flows that have cooled slowly.

In the eastern United States the most conspicuous examples are found in the intrusions and flows of " trap " of the Triassic formations stretching from Nova Scotia to Georgia. Through faulting and erosion they now give rise to definite topographic features, such as the ridges in Connecticut and the Palisades opposite New York City. Similar masses of these rocks are found in the Lake Superior region and in the great lava flows of the western United States. In all these occurrences they are associated with, and pass into, the fine-grained forms of basalt. These larger occurrences of dolerite mostly contain pyroxene as the dominant ferromagnesian mineral and are largely the rock called " diabase " by petrographers, while those in which hornblende is dominant are mostly confined to dikes and smaller intrusions, especially in the older rocks.

Dolerites are also very common rocks in dikes and intrusive sheets at various localities in Great Britain. In the north of Scotland and Ireland they are often extrusive and associated with fine-grained basalts. They are, in fact, very common rocks in all parts of the world.

Relation to Other Rocks. — Alteration. From what has been said it is easy to see that the dolerites are a class of rocks based largely on convenience. They form a transition group, based on texture, between the diorites and gabbros and the aphanitic basalts.

Rocks may occur in which, instead of hornblende or pyroxene, biotite is the dominant mineral associated with the feldspar. Such rocks are not very common but are sometimes found, especially in dikes and sheets, and with quite fine grain. They form the *mica trap*, or minette, mentioned later under basalt.

The pyroxenic members of this group, by regional metamorphism, become converted into hornblende rocks, generally into hornblende schists, and both varieties by alteration may produce chlorite and pass into the so-called "greenstones." These alterations are quite similar to what has been described under gabbro. By weathering they become brownish and discolored and ultimately yield brown ferruginous soils.

Uses. The rocks of this group are too dark and somber for general use in fine architectural or interior work, except for monumental purposes. The "trap" of the Eastern States has been considerably employed in rough masonry, and where good natural joint faces can be used for wall surfaces, the brown weathering color gives pleasing effects. The toughness of the trap has caused it to be considerably used for block paving and as crushed stone for road making.

Peridotite — Pyroxenite — Hornblendite

Composition. Under this group are comprised all of those granular ~~igneous rocks~~ composed of ferromagnesian minerals ~~alone, or~~ in which the amount of detectible feldspar is so small as to be entirely negligible as a component, and in which the mineral grains are sufficiently large to be determined. The chief minerals that form these rocks are olivine, pyroxene of both the augite and hypersthene varieties, and hornblende. These may occur alone or in various mixtures, and on the basis of the minerals present the rocks have been subdivided into types, some of the more prominent of which are as follows:

Pyroxenes and Olivine	Peridotite
Hornblende and Olivine	Cortlandtite
Olivine alone	Dunite
Pyroxenes alone	Pyroxenite
Hornblende alone	Hornblendite

The first three, which contain olivine, are comprised under the general name of peridotites, from peridot, the French word for olivine. All the different types, while they sometimes occur independently, also occur together, with transition forms grading into one another, and it is difficult, and sometimes impossible, to distinguish them megascopically; therefore they are best treated together as one general group and not as separate rocks.

Besides the minerals mentioned, a brown biotite sometimes occurs in these rocks, giving rise to the variety called *mica peridotite.* Additional accessory minerals, some of which are common and some confined to certain occurrences, are ilmenite, spinels, of which chromite is of importance, and garnet.

Texture. The texture is granitoid or granular; its appearance depends somewhat on the minerals present and their arrangement. When pyroxene or hornblende is the dominant mineral the grain is often very coarse and may exhibit large cleavage surfaces. Dunite is not often coarse-grained; it commonly has a sugar-granular texture like many aplites, sandstones, marbles, etc. Porphyritic texture is rare or wanting. A common texture is one in which the cleavage surfaces of the pyroxenes or hornblendes are seen to be spotted with grains of olivine included in the larger crystal. Such a spotting of the shining cleavage surfaces of one mineral by smaller included crystals of another, which lie in random orientation either with respect to one another or to their host, is called luster mottling or *poikilitic texture.* It is sometimes well exhibited in these rocks. The included crystals are, of course, older than their host.

Chemical Composition. This varies according to the minerals in the rocks, but general characters are the very low silica, the small amount or virtual absence of alkalies and alumina, and the large quantities of iron and magnesia.

ANALYSES OF PERIDOTITES, ETC.

	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	H_2O	XyO	Total
I	40.1	7.8	7.3	8.6	23.7	6.5	1.2	0.5	4.0	0.6	100.3
II	43.9	1.6	8.9	2.6	27.3	6.3	0.5	...	8.7	0.3	100.1
III	53.2	1.9	1.4	7.9	20.8	13.1	0.1	0.1	1.0	0.5	100.0
IV	46.4	10.8	5.9	5.6	22.2	3.7	0.3	1.2	3.8	...	99.9
V	38.4	0.3	3.4	6.7	45.2	0.4	0.1	...	4.3	1.4	100.2

I, Peridotite, Devonshire, England; II, Peridotite, Baltimore County, Maryland; III, Pyroxenite, Oakwood, Maryland; IV, Hornblendite, Valbonne, Pyrenees; V, Dunite, Tulameen River, British Columbia. XyO = Small quantities of other oxides.

Color. The color of these rocks ordinarily varies from dull green to black. The dunites, which are practically composed of the one mineral olivine, are as a rule much lighter. They may show various shades of light green, medium yellow, and light brown, passing into one another, and from these through dull yellowish green into dark green. They may thus be exceptions to the general rule that ferromagnesian rocks are dark-colored.

Occurrence. — Relation to Gabbro. The peridotites and allied rocks sometimes occur independently as dikes, sheets, laccoliths, or small intrusive stocks. In this way, as small isolated occurrences they have been found cutting the Paleozoic rocks, usually in a more or less altered condition, at Syracuse and other localities in New York State, in Kentucky, in Arkansas, and elsewhere. Generally speaking, however, they are most likely to occur in connection with greater intrusions of gabbros. Sometimes they form facies of the gabbro mass, with transitions between the two; sometimes they cut the gabbros in dikes or are found in small intrusions in their neighborhood. This dependence upon the gabbros has led to their being regarded as products of differentiation of the gabbro magma in which they represent the lamprophyres of other rock groups. A great number of such occurrences are known in all parts of the world where gabbros are common rocks.

Dunites occur in masses that are intrusive in the gneisses of western North and South Carolina and Georgia. Associated with them are smaller amounts of other peridotites and pyroxenite. These occurrences are of importance on account of the deposits of corundum of commercial value associated with them. The mineral is thought to have formed in them in the same manner as described under syenite. Dunite also occurs in considerable masses in the Ural Mountains of Russia and in New Zealand, especially in the Dun Mountains, from which came the name. Pyroxenite and hornblendite are comparatively rare and of relatively small geologic importance.

Alteration. — Serpentine. The peridotites are extremely liable to alteration, so much so that unchanged occurrences are not at all usual. The most common form of alteration is that in which the olivine and other magnesian silicates are changed to serpentine. Such serpentinized peridotites are called serpentines, the name serpentine being thus used both as the name of a mineral and of a rock.

Other magnesian minerals, such as talc, are also formed by the alteration of peridotites, but the alteration to serpentine is the most important. All stages of transition to pure serpentine occur, and studies which have been made in recent years show that a large part, perhaps the greater part, of the occurrences of serpentine the world over are to be assigned to the alteration of peridotites and pyroxenites.

The serpentine ultimately weathers down into brown ferruginous soils which, on account of their lack of potash, do not favor vegetable growth and are therefore barren.

As a Source of Valuable Minerals. The magmas that form the peridotites usually carry small amounts of chromic oxide which often crystallizes with iron oxide to form the mineral chromite, $FeCr_2O_4$, one of the spinel group. It is often seen in dunite and usually forms small, black, brilliantly lustrous grains. In some peridotites it is concentrated in such an amount that it becomes a useful ore, supplying the chromium used in the industries.

The olivine of these rocks has been found by analysis to contain a minute amount of nickel; when they change by weathering it sometimes happens that this nickel is concentrated in the form of nickel silicate, occasionally in amounts sufficient to form deposits of value as a source of this metal, as in Douglas County, Oregon, and in the Island of New Caledonia.

The peridotites, and to a minor extent their allies the gabbros, are also the source of platinum, which occurs in them as the native metal; by the decay of the rock it is washed down and, like gold, concentrated in alluvial deposits. The precious garnet, pyrope, used as a gem, also comes from a decayed and serpentinized peridotite from Bohemia, South Africa, etc. Lastly, the diamonds of South Africa have their source in greatly altered peridotite rocks. This altered rock, which was originally a mica peridotite, is known as *kimberlite*, or, by the miners, as "blue ground." Formerly it was held that the carbon forming the diamonds was derived from the carbonaceous shales through which the magma passed; now it is known that it was original in the magma and that the diamond is a true crystalline constituent of the igneous rock like any other of its accessory minerals.

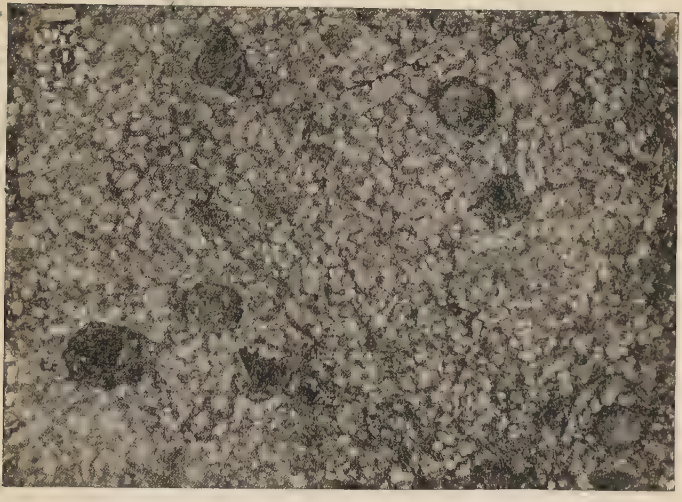
Porphyries

Definition. These rocks may be divided into two main groups: one in which, on account of its coarse texture, both the phenocrysts and the grains of the groundmass can be determined, or the determinable phenocrysts form so large a proportion of the rock that a good idea of its mineral composition can be obtained and the small amount of aphanitic groundmass may be neglected; and a second group in which the amount of aphanitic groundmass is large and the phenocrysts are not abundant enough to determine safely the mineral character of the rock. It is the first of these two groups which is described in this section, the one that we may call the group of determinable porphyries; the second group will be considered later in connection with the aphanitic igneous rocks — the felsites and basalts — of which they form a porphyritic variety.

In this first group, porphyries are mainly confined to the feldspathic division of the igneous rocks, apparently for the reason that the magmas which furnish the ferromagnesian rocks have relatively so low a viscosity and crystallize so readily that they are not likely to form porphyries, while under the same conditions the feldspathic rocks often do so readily. Thus granite porphyry is very common, while gabbro and peridotite porphyries are so rare as to be of no practical importance. In the group of aphanitic igneous rocks, porphyries of both divisions are common. The rocks to be treated then are granite porphyry, syenite porphyry, and diorite porphyry. There are so many points in which they are similar that they are best treated as a group.

Granite Porphyry. This consists of distinct phenocrysts of quartz and of feldspar in a granular groundmass of the same minerals, in which the grains can be determined as such, or in which the abundance of the quartz and feldspar phenocrysts gives a distinct granite-like character to the rock although the groundmass is aphanitic. The rock may consist of these minerals alone, or very nearly so, or biotite and hornblende may be present, perhaps in considerable amount. The biotite and hornblende may occur separately or together, though hornblende alone is rare. They may be distinct phenocrysts, usually smaller than the quartz and especially than the feldspar, and they may also occur in the groundmass, in which case the tiny specks of biotite are most easily detected. The predominant feldspar is orthoclase; as the amount of associated plagioclase increases the granite porphyry grades into quartz monzonite porphyry and granodiorite porphyry. In

PLATE 19.



A. GRANITE PORPHYRY, MONTANA.

B. SYENITE PORPHYRY, MONTANA.

C. SYENITE PORPHYRY, NORWAY.

recent years porphyries of these kinds have become of great economic interest, inasmuch as they constitute the country rock at many of the great disseminated copper deposits, as at Bingham, Utah, Santa Rita, New Mexico, etc.

When the groundmass is so coarse as to be equivalent to an ordinary granite it is customary to speak of the rock as porphyritic granite, as explained under granite.

Syenite Porphyry. This rock consists of distinct phenocrysts of orthoclase in a groundmass, which, if determinable, must be made up mainly of grains of feldspar with very little or no quartz. If the groundmass is not determinable the amount of phenocrysts must be large enough to give the rock a distinctly syenitic character. The ferromagnesian minerals, biotite, hornblende, and pyroxene, while they may be absent or practically so, are usually present, either as phenocrysts, or in the groundmass, or both. They occur separately or together, but the combination of all three or of biotite and pyroxene is not so common as that of biotite and hornblende.

The rock defined above is that which corresponds to the common one of the two varieties of syenite described on page 225 and following, and represents it in porphyritic development. It is not a common rock. Nephelite syenite porphyry is known but is a very rare rock.

Diorite Porphyry. Diorite porphyry is composed of phenocrysts of plagioclase feldspar and of hornblende, biotite, or pyroxene, either separately or together, in a determinable groundmass of the same minerals; or if the groundmass is not determinable the diorite character must be clearly shown by the abundance of the phenocrysts.

If quartz also occurs among the phenocrysts, the rock is termed a *quartz diorite porphyry*. It is likely to resemble closely a granite porphyry or the varieties of porphyry intermediate between granite porphyry and quartz diorite porphyry, namely, quartz monzonite porphyry and granodiorite porphyry.

Phenocrysts of Porphyries. As the phenocrysts of porphyries have crystallized freely in the fluid magmas, they generally show distinct crystal shapes, such as are described in the foregoing part devoted to the rock minerals. A few words in regard to their crystal habits may be added here. *Quartz*, as a phenocryst, tends to take the form shown in Fig. 43, but is usually ellipsoidal or spherical; the crystals may be a half inch in diameter but are usually much smaller, the size of coarse shot or peas. The *feldspars* tend to assume the forms shown by Figs. 5–7; they are often twins, Fig. 8; they are white, pink to red, or yellowish and gray; if feldspars of two colors are present and one of them has a reddish tone it is probably orthoclase, the other albite or a soda-lime feldspar. They not infrequently form very large phenocrysts, an inch or even more in length; many of the model-like feldspars seen in mineral cabinets are phenocrysts obtained from porphyries. *Hornblende* occurs in dark greenish or black prisms, usually elongated, and sometimes quite slender and with glittering cleavage surfaces if fresh; the terminal faces are poor or wanting; sometimes the hornblende is weathered out and only a rusty mass left in its place. *Pyroxene* is also dark green to black, in short, stout prisms, and commonly its cleavage and crystal faces lack the luster of hornblende. The method of distinguishing them has already been explained. Rusty spots also show the former presence of pyroxene, but less commonly than that of hornblende. In size both tend to be small, compared with feldspar. *Biotite,* as a phenocryst, is in six-sided tablets with fine basal cleavage, black to bronze-brown in color. In these rocks its crystals are usually small.

General Properties. The *chemical composition* of these porphyries is similar to that of the corresponding kinds of granular rocks previously given and need not be repeated. Their specific gravity and modes of alteration and conversion into soil are the same. The *jointing* depends largely on the mode of occurrence; it is generally platy or small cuboidal, or forms small parallelopipedons with acute angles, in the feldspathic porphyries of dikes and sheets, and larger blocks in the greater intrusions; the doleritic porphyries tend to have columnar jointing.

Occurrence. The porphyries of this class commonly occur as minor intrusions: as dikes, sills or intrusive sheets, laccoliths, and sometimes in volcanic necks. They are also not uncommon as marginal facies of intrusive stocks and of batholiths of granite, syenite, etc.; they here represent an endomorphic contact modification; and in traversing areas of such rocks, if it is observed that they are becoming porphyries with finer grain, approach to the contact should be suspected. They may also occur in extrusive lava flows, especially if these are very thick and massive, but in this mode of occurrence they are generally replaced by the fine-grained felsite and basalt porphyries described in a later paragraph.

It is impossible to give any list of localities for these rocks, because they are far too common; they are found wherever erosion has exposed the older crystalline rocks and where igneous activity has displayed itself. Where larger stocks and intrusions have occurred, these porphyries are especially likely to be present, some cutting them as dikes, some extending from them in apophyses, and some in dikes sills, etc., as satellites grouped about them.

Perhaps the most notable occurrences of these rocks are in the great laccoliths of the Rocky Mountain region, in Colorado, Utah, Wyoming, and Montana. These laccoliths are generally composed of granite or syenite porphyries and some of these masses are a mile in thickness by several in breadth, but they are often smaller. In these regions they often form immense sills, several hundred feet in thickness.

Aphanitic Igneous Rocks

In the preceding groups of igneous rocks it is assumed that all or most of the component grains of the rock can be determined and the mineral constitution safely established. In the present group it is assumed that the texture of all of the rock, or of the greater part of it, is so fine-grained that this cannot be done. No definite line can be drawn between the two groups; whether a given rock belongs to the one or the other, is often largely a matter of opinion, dependent upon the experience of the observer, his knowledge of rocks and minerals, his power of observation, keenness of eyesight, and the excellence of his lens.

As has already been explained, in the section treating of the classification of igneous rocks, these aphanitic varieties are divided into two groups on the basis of color, i.e., into the dark to black *basalts* and the lighter-colored *felsites;* each of these has a porphyritic subdivision. Of these the felsite will be considered first.

Felsite and Felsite Porphyry

The felsites include all those extremely fine-grained igneous rocks that are of stony texture and not evidently glassy. They show all colors except dark gray, dark green, or black, these latter belonging to basalts. Felsites normally show light shades of color: white, which is not very common, light to medium gray, light pink or red to dark red, pale yellow or brown, purple or light green. With the lens it can be frequently seen that they consist of minute mineral grains, too small for determination, and the texture is then very fine granular. Sometimes the grains may be entirely too fine to be seen; the rock has then a dense, horn-like or flinty aspect, appearing like a homogeneous substance, and is very likely to have a smooth conchoidal fracture. Again, especially in surface lavas, the texture is more or less porous and the fracture surface of the rock rough and hackly, with a harsh feeling. A pronounced cellular or vesicular structure, common in basalts and in glassy rocks, and illustrated in Plate 8, is not very common in this group. The surface lavas not infrequently show fluidal bandings and streakings, more or less flat lenticular, and often curved or curled, due to flowage; these are clearly brought out on weathered surfaces, as illustrated in Plate 22.

The division of the aphanitic igneous rocks into felsites and basalts is based on color, and not on mineral composition, since the latter cannot be determined. Nevertheless the felsites as classed above are, in general, feldspathic rocks, and they represent, in aphanitic form and often as lavas, those magmas which, under different geologic and physical conditions, would have produced granites and syenites, while the basalts correspond to diorites, gabbros, and dolerites, as already explained under classification.

Where these rocks are of medium gray or drab color, it is often difficult to know whether to assign them to the felsites or basalts. This happens especially when they are very fine-grained. If the rock be sharply examined with a good lens, it may be seen that many tiny chips and flakes, only partly formed and yet in the main a part of the mass, lie upon its surface, their thin edges separated from it by a flat underlying crack. It will be observed that their thin edges are very much lighter in color than the rock upon which they lie, and are translucent to light; indeed, they will often appear practically white, even when the rock is a dark gray or stone color. This is a peculiarity of those aphanitic rocks that are chiefly composed of feldspar and are, therefore, to be classed as felsites; it is not shown at all, or only in a very small degree, by the basalts. The reason for this is that, although they may be colored by a pigment, the feldspars are transparent to translucent minerals and a rock composed mostly of them is also megascopically translucent on thin edges, while one composed mostly of ferromagnesian mineral particles is not, since these minerals are either opaque, or practically so, from the megascopic standpoint. The same effect may be observed on the very thin edge of a flat chip broken from the rock. In case the individual grains are large enough to be seen with the lens, if these are transparent or translucent with light colors, it may be assumed in general that they are mainly feldspar, the ferromagnesian mineral grains being mostly dark, dull, to opaque. Olivine, with its yellow-green color, however, is an exception and must not be confused with feldspar. It will also be noted that under a good lens the mineral grains, or many of them, appear much lighter in color than the rock appears to the eye in its general effect.

These tests, while they cannot be held to be exact, will often prove of service in helping to decide, in doubtful cases, whether a rock belongs to the felsites or the basalts, for the division between them, while based primarily on color, is due to a mineralogical difference as well.

It is assumed in what has been said regarding these rocks that one is dealing with reasonably fresh, unaltered material, not rocks that have been long exposed to atmospheric agencies and are weathered into dull ferruginous material.

Varieties of Felsite. From the megascopic standpoint the different varieties of felsite that can be recognized are those due to color and texture alone; the petrographer by the use of the microscope on thin sections is, however, able to determine the different kinds of minerals that form the minute grains and to divide and classify these rocks on a mineralogical basis, just as was done with the coarse-grained rocks, the grains of which could be seen and determined by the eye.

Felsite Porphyry or Leucophyre. While there are felsites that contain no porphyritic crystals, it is much more common for them to contain phenocrysts. These may be very few, scattered and isolated, or they may be abundant. They may be quite evenly scattered, or they may be collected in groups. The phenocrysts may be salic, in which case they are *quartz* or *feldspar*, or they may be ferromagnesian: *biotite*, *hornblende*, or *pyroxene*. For the appearance and properties of these phenocrysts see the description of them in the former group of porphyries, page 250.

In the association of these phenocrysts, while all of the above minerals occur at times alone, there are likely to be two or more present. The presence of quartz and feldspar with the others is not uncommon; if a dark mineral is associated with the quartz it is most likely to be biotite; hornblende is less common, and pyroxene very rare. Feldspar and hornblende, pyroxene and feldspar are very common. In general, feldspar is the most common phenocryst.

The general term of *felsite porphyry* may be given to these rocks, or this term may be changed to *leucophyre* (from the Greek, λευκός — white), meaning light-colored porphyry.* If no mineral qualifier is used with this it is understood that the phenocrysts are of feldspar, since this is most general. If they are of quartz, biotite, hornblende, etc., we have the following terms.

Quartz felsite porphyry or *quartz leucophyre.*
Hornblende felsite porphyry or *hornblende leucophyre.*
Biotite felsite porphyry or *biotite leucophyre.*
Augite felsite porphyry or *augite leucophyre.*
Hornblende-feldspar leucophyre.
Quartz-feldspar leucophyre.

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* As suggested in the "Quantitative Classification of Igneous Rocks." Messrs. Cross, Iddings, Pirsson, and Washington, p. 184.

These examples are sufficient to show how mineral qualifiers may be used in designating the phenocrysts of these rocks, and how these may be combined, if desired, to give expression to considerable descriptive detail. Other examples will readily suggest themselves.

General Properties. The *chemical composition* of felsites is variable, depending, like the sub-varieties enumerated above, on the prevailing minerals. Some analyses correspond to those of granite already given; these contain free quartz; others are like the analyses of syenites and such must contain little or no quartz. If the amount of lime is small, the silica below 60 per cent, and the alkalies high, the rock must be mostly composed of alkalic feldspar and probably nephelite is present. The *specific gravity* ranges from 2.4 to 2.65 and is usually lower than that of granite and syenite. The *jointing* is platy, or in small blocks; columnar structure also occurs, but is not so common or so perfect as in basalts. In normal *weathering* to soil these rocks become discolored, brownish, reddish, etc. The ferromagnesian mineral generally disappears, leaving a rusty spot or cavity; the rock crumbles into débris, at first largely through mechanical disintegration. Finally the feldspars change to clay, as described under granite, and the change to soil is complete. Where hydrothermal action takes place, as in the vicinity of ore veins, the felsites are commonly changed to whitish rocks containing abundant sericite, the fine scaly form of muscovite.

Occurrence. Felsites occur intrusively as dikes and sheets, and in places as the endomorphic contact facies of larger intrusive masses, whose main character is that of granite, granite porphyry, syenite, etc. They indicate intrusions of magma into cold rocks, and when they occur as intrusions, these are usually relatively small, or narrow.

They are much more common extrusively, as lava flows and sheets, and they sometimes cover very large areas, many hundreds and even thousands of square miles in extent. In these cases, and especially in volcanic cones or their eroded remnants. felsites are usually interbedded with tuffs and breccias.

While it would be impossible to give any adequate list of actual occurrences it may be mentioned that felsites as intrusives occur extensively in eastern North America, among the older rocks in the Atlantic border States, along the eastern front of the Appalachian uplift; as extrusives they occur in Maine, in the White Mountains, in Pennsylvania, and to the southward. They occur also in Wisconsin. Much more extensive in western America is their effusive occurrence throughout the whole of the Cordilleran tract, where they play an important rôle in the upbuilding of many of the ranges, and sometimes occupy large areas. Here all the different varieties are found, as for instance rhyolite in the Yellowstone Park, in Colorado, and elsewhere; andesite in the lofty volcanoes of the Cascade Range and in those in South America, and in the eroded ones of the main chain of the Rocky Mountains; and the rare variety phonolite at Cripple Creek, Colorado, and in the Black Hills of South Dakota.

The felsites are just as extensively found in other parts of the world. In Europe they are well distributed as lavas, occurring thus in northern Wales, in the Lake district of England, and in northern Ireland. These are the varieties called rhyolite and andesite. They are found in western Germany, in France, Italy, and in Hungary. Wherever volcanic outbreaks have taken place extensively, felsite lavas occur.

Felsites and felsite porphyries are often found in the form of narrow dikes that traverse the larger stocks or intrusions of coarse-grained rocks, such as granite, syenite, etc., or the rocks in their immediate vicinity. They are here generally complementary to dark dikes, mentioned later as lamprophyres, and have received special names from petrographers. Thus we have *bostonite* (allied to trachyte), *tinguaite* (allied to phonolite), and many others. Note in this connection paragraphs on complementary rocks, on aplite, and on lamprophyres.

Basalt and Basalt Porphyry

The basalts include those aphanitic igneous rocks, of very dark color, the fabric of which is so fine that the constituent grains either cannot be perceived by the eye or with the lens, or, if seen, are too small to be recognized, and which are of stony but not of glassy texture. The color varies from grayish black or dark stone color, greenish or purplish black to pure black. As a rule, the basalts do not show translucency on the edges of thin flakes as described under felsite. When not cellular and very fine-grained, they have a uniform dull, soft, almost velvety appearance, and do not show the horny. flinty, or greasy luster of many aphanitic felsites.

The study of thin sections of these rocks shows that in general they are composed of minute crystal grains of soda-lime feldspar (generally labradorite), pyroxene, and iron ore, very often with more or less olivine, and sometimes with biotite or hornblende. Nephelite or leucite may accompany the feldspar, or replace it, giving rise to varieties which have received special names. These varieties, although very interesting from the standpoint of theoretical petrography, are comparatively rare and relatively of small importance in a general geological way.

Being composed of the same minerals, these rocks represent, in aphanitic form and generally as surface lavas, those magmas which under different physical conditions would have solidified as gabbros, peridotites, dolerites, and (in part) diorites. A large part of the dolerites in fact are transition rocks between basalts and gabbros, as previously mentioned in the description of dolerite, and instances may be found in the same rock mass where the gradation into dolerite may be seen.

Basalt Porphyry. While porphyritic varieties of basalt are not uncommon rocks, it may be said in general that this type of texture plays a far less important rôle in this group than in the felsites previously described, owing probably to the low viscosity and easy crystallization of the magma. One exception to this, however, is the presence of olivine, which is very likely to occur scattered through the basalt in transparent yellowish or bottle-green porphyritic grains, averaging about the size of moderately coarse shot. The mineral is so common (indeed at one time a rock was not considered a basalt unless it contained olivine) and produces in general sc little of a striking porphyritic effect, that it is rather the custom to ignore it in this respect, and to term such rocks olivine basalt rather than olivine basalt porphyry.

The chief minerals that may occur as phenocrysts are feldspar and pyroxene; hornblende and mica are much less common. The feldspar is commonly labradorite; it occurs in elongate tabular forms, either singly, or in twinned groups. The pyroxene is the variety augite; it is black, sometimes shining, sometimes dull, and is in short thick prisms or prismoids, as illustrated under pyroxene. The hornblende also is black and has its usual shining and good cleavage. Biotite is in six-sided tablets.

These rocks are named in accordance with the prevailing phenocryst, for example, *augite basalt porphyry.* Instead of the term basalt porphyry the name *melaphyre,* meaning "black porphyry," may be used as more convenient* and we should then have *feldspar melaphyre, augite melaphyre, biotite melaphyre,* etc.

General Properties of Basalt. The *chemical composition* of basalt varies with its mineral composition; in general it is of the same nature as that of gabbro previously given, as may be seen from the following analysis of a basalt from California, which will serve as an example.

SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	H_2O	XyO	Total
51.9	15.3	3.1	3.6	8.7	7.4	3.3	2.5	2.5	1.7	= 100.0

The *specific gravity* is high, about 3.0 (2.9 to 3.1). The *jointing* is platy or columnar; indeed, the best examples of this structure are found in basalt and there are many notable occurrences of it in all parts of the world, the Giants' Causeway on the north coast of Ireland being one of the best known. This structure is seen in Plate 11. Sometimes basalt on weathering develops a singular "spheroidal" structure, forming rudely spherical exfoliating masses.

Varieties. In the fine-grained non-porphyritic basalts there is little opportunity for variation, save that which is based on a change from the compact into the porous or cellular structure. This last is particularly common in lava flows, especially in their upper and their bottom portions, and has been illustrated on Plate 8. It is particularly in these basalts that the amygda-

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* Quantitative Classification of Igneous Rocks, p. 185.

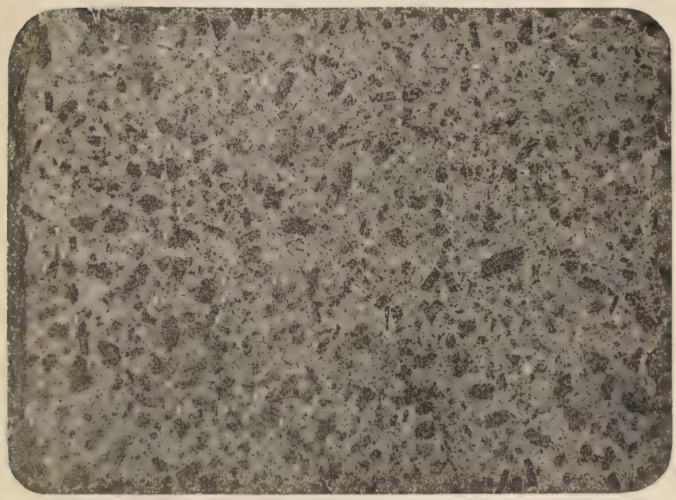
loidal structure, also illustrated on the same plate, occurs. The minerals filling the cavities in basalt are commonly quartz, calcite, chlorite, or zeolites; among the zeolites, analcite, natrolite, stilbite, and heulandite may be particularly mentioned. Such rocks are termed *amygdaloidal basalt.* In a number of places, and particularly in western America, basalts containing visible grains of quartz have been found as surface lavas. One of the most noted of these is the basalt flow from the Cinder Cone, near Lassen Peak in northern California, which is filled with angular pieces of quartz of varying sizes. As many of these basalts correspond in composition to gabbros and dolerites, the presence of the quartz in them appears anomalous, since magmas so low in silica, as may be seen by referring to the analyses of gabbro, would not be expected to develop free quartz on crystallizing. Some petrographers therefore think that these are fragments of quartz rock in the depths, which have been torn loose and distributed through the magma, while others regard them as a primary crystallization, produced under exceptional conditions of pressure and mineralizers. These rocks have been called *quartz basalts.*

The porphyritic varieties have been described above, but it may be mentioned that a variety containing distinct and sometimes large crystals of labradorite feldspar has been called *labradorite porphyry.* The greenish-black porphyry from Greece, employed by the ancients (porfido verde antico), is a somewhat altered example of this type. A variety containing rather large and distinct crystals of augite has been termed *augitophyre.*

The name *trap* has been used in a general way as a field term to designate the rocks called here basalts, and also dolerites. As thus employed it would mean any dark-colored, heavy, igneous rock of undetermined mineral composition. Thus the dolerites and basalts of the Newark formation along the Atlantic Coast have been termed "Triassic traps"; the great effusives of western India are known as the "Deccan traps."

PLATE 20.

A. Labradorite Porphyry.



B. Augitophyre.

VARIETIES OF BASALT PORPHYRY.

Lamprophyres. The ferromagnesian complementary rocks, occurring in dikes and sheets in or around stocks of granite, syenite, etc., and often called "trap" dikes, etc., belong for the most part under this heading of basalt. Their origin and relations have been discussed in the preceding part of this work and they have been mentioned again under granite. They very often contain phenocrysts of the ferromagnesian minerals, olivine, augite, hornblende, and biotite, either separately or together, and sometimes of very large size. These phenocrysts are embedded in a groundmass that is usually aphanitic and dark-colored. According to the variations in the minerals, as shown by the microscope, a large number of different types have been named by petrographers, but the distinctions between them cannot ordinarily be made megascopically. For field work they may be treated simply as basalt porphyries as described above, and termed augite melaphyre, biotite melaphyre, etc. It may be mentioned that biotite melaphyre frequently occurs as dikes associated with granite, and has been called *mica trap* or *minette.* A hornblende melaphyre occurs in the same way with many syenites and nephelite syenites; it has quite a wide distribution in New England and has been termed *camptonite.*

Olivine Nodules. It frequently happens that basalts, in addition to the ordinary crystals of olivine, contain yellowish or green lumps, or nodules, made up of grains of this mineral. Grains of other minerals, such as pyroxene, spinel, etc., may be present in them. These lumps may vary in size from a pea to masses as large as one's fist, or even larger. They are generally rounded, but many are distinctly angular in shape. Their origin is somewhat problematical; some hold that they are merely agglomerations of the earlier-formed crystals in the liquid magma, while others regard them as fragments of rock (dunite) torn off below and brought up in the magma.

Exotic Minerals. Basalts sometimes contain unusual minerals, which do not appear in the ordinary varieties and whose origin in them must be ascribed to unusual conditions or to the abnormal composition of the magma. The quartz basalt mentioned above is one of these uncommon varieties. Another is the iron-bearing basalt of Greenland, which contains small to large masses of native iron, much like the iron found in meteorites. By the use of a solution of copper sulphate, specks of native iron have been found in basalts from other places. The Greenland basalt also contains graphite. Corundum, in the form of sapphire, has also been found in basalts, and a dike in Montana has furnished a quantity of valuable gems. Here also may be mentioned the occurrence in places of native copper, especially in the Lake Superior district, where the metal occurs in dolerites and basalts and in connection with them, in quantities which have made this district one of the most important sources of the world's copper supply. The copper is not of direct igneous origin but has been brought up and deposited in the basalts by ascending hot-water solutions.

Weathering and Alteration. In many volcanic regions, where basalts have been subjected to exhalations of steam or to heated water, the minerals containing ferrous iron, such as magnetite and olivine, become reddened through change to ferric oxide. Sometimes the olivines alone are reddened; at other times the whole rock becomes deep red to reddish brown. Such rocks may be difficult to distinguish in the field from red felsites, and may even have to be classed with them. Sometimes, however, the association with other rocks, the retained form of phenocrysts, and the good amygdaloidal structure, rarely seen in the most common felsites, may help one to recognize the original character of the rock.

The normal weathering of basalt in a temperate, humid climate gives rise to clay and iron hydrates. In a monsoon climate it turns brown through oxidation and eventually falls away into brownish ferruginous soil, the *laterite* of India, from which all but the hydroxides of iron and aluminum have been leached.

Under processes of metamorphism the basalts act like the gabbros and dolerites previously described, and give rise to "greenstone" and to greenstone schists and amphibolite.

Occurrence of Basalt. As intrusive rocks, sheets, and especially dikes, basalts of various types, both non-porphyritic and porphyritic in texture, are so common in all regions where igneous rocks occur that they need no further mention. As extrusive lavas, in the form of flows and extended sheets, they are of much greater geological interest and importance. There is scarcely any volcanic region in the world that does not exhibit them in greater or lesser amount, and in some regions, as in the lava fields of the Columbia in western America and in western India, they have been poured out in stupendous masses, so that tracts of country nearly 200,000 square miles in extent have been covered thousands of feet deep. A similar great field existed in northern Great Britain, and its remnants, portions yet saved from the eroding edge of the Atlantic, form in great part the northern British Isles.

Leucite Rocks. Basaltic rocks in which the feldspathoid minerals, nephelite or leucite, are present, either accompanying the feldspar or taking the place of it, while not common, have in some regions a considerable development. Ordinarily these minerals are in the groundmass, and only to be detected by the microscope, and such rocks in the field must be classed as regular basalts. In central Italy, however, the leucite rocks have a great development, and the leucite crystals often appear as phenocrysts as large as peas, or larger at times, and are easily recognized. They are leucite basalt porphyries or leucite melaphyre. For the properties of leucite, its description under rock minerals should be consulted. According to the other minerals present, several different types of these rocks are distinguished and named. Some of them are so light-colored that they might be classed as varieties of felsites. Outside of Italy these leucite rocks are very rare, occurrences being known in the Rhine district, in central Montana, in western Wyoming, and more especially in Java, but since the well-known lavas of Vesuvius are composed of them, they are mentioned here.

Glassy Rocks

In the felsites and basalts the use of the microscope on thin sections would frequently show that a certain amount of glass, uncrystallized and solidified magma, is present in them, acting as a cement to hold the mineral grains together. This cannot be detected megascopically, and the term glassy rocks, as here used, is applied only to such as are entirely of glass, or, if partly crystalline, contain glass in such amounts and in such circumstances that it is visible and evident to the eye.

The conditions that will cause a magma to solidify as a glass are evidently those unfavorable to crystallization, i.e., extremely quick cooling in the first place, and probably to some extent the rapid loss of mineralizers in the second. This has already been discussed in connection with the texture of igneous rocks. These conditions are best realized when the magmas are poured out on the surface as effusive lavas; and just as we associate a coarse-textured, entirely crystalline, granular rock, such as granite, with an intrusive or deeply seated origin, so conversely we associate glassy rocks with an extrusive one. Indeed, while it is true that dikes may sometimes show glassy selvages along their borders, when they have been intruded into cold rocks, or may be wholly of glass when the exposure is near the original surface, as in recently denuded dikes in volcanic regions, this is so uncommon that in general we may regard a rock composed partly or wholly of evident glass as of extrusive origin; that is, we may assume that it was originally a surface lava, although it may have been buried under later formations.

Any of the different magmas, varying as to composition, may form glassy rocks if chilled with sufficient rapidity; but petrographical research has shown that, while glassy forms of the felsite lavas are common, those corresponding to basalt are rare and of inconsiderable volume. The reason for this is that the magmas which furnish felsites, or the granite and syenite which correspond to them, have relatively high viscosities near their freezing-points, and as the magma cools down and approaches the freezing-point, it becomes so enormously viscous that the free movement of molecules necessary for crystallization is prevented. This is due to the large amount of silica that such magmas contain, which has a strong effect in promoting viscosity. The presence of water in the magma tends to counteract the effect of the silica and to make the magma more fluid and thus to help crystallization, but when the magma is poured out on the surface the water is rapidly lost, with resultant increase in viscosity. On the other hand, the basaltic magmas, or those corresponding to gabbro or diorite in part, which contain relatively low silica and high iron and magnesia, have a much lower viscosity as they approach the freezing point, thus permitting easy crystallization and the assumption of stony texture and appearance. Consequently those glasses that have the highest percentage of silica and correspond to granite in composition are the most common ones.

Classification of Glassy Rocks. As already stated in the classification of igneous rocks, we may divide the glassy rocks into two groups: one in which the rocks contain distinct crystals or phenocrysts embedded in a glass base, or, in short, porphyritic varieties; and second, rocks in which there are no distinct phenocrysts and which consist of either pure glass, or glass more or less filled with spherulites or lithophysæ, as described later. The second group is again subdivided according to luster and structure. In accordance with this we have the following classification:

Glass with few or no phenocrysts	*Obsidian*, strong, bright, vitreous luster.
	Pitchstone, dull, pitchy, or resinous luster.
	Perlite, apparently made of small spheroids.
	Pumice, cellular structure, glass froth.
Glass more or less filled with phenocrysts	*Vitrophyre*, glass porphyry.

Obsidian. This is pure, solid, natural glass, devoid of all apparent crystal grains, or nearly so. It has a bright luster like that of artificial glass. It usually has a jet-black color; but when the edges of thin chips are examined against the light it is generally seen to be transparent or translucent with a more or less smoky color, and a lens will frequently show that the coloring matter is more or less collected into fine parallel streaks, bands, or threads, as if drawn out in the flowage.

Less commonly the glass is gray, or Indian red, or rich brown, and this color is sometimes mixed with the black in bands and strings, which, kneaded through it, produce a marbled effect. The microscope shows the black glass as colorless and filled with tiny, black, dust-like particles; they are probably specks of magnetite, which represent the beginnings of crystallization, and, diffused through the glass, they act as a pigment, coloring it black. Sometimes they have been oxidized to hematite dust and the color is then red or brown.

Obsidian has a remarkable conchoidal fracture (illustrated in Fig. 4, page 28) due to its homogeneity and lack of structure. It was this quality that made the substance so highly valued by primitive peoples, for it enabled them by chipping to work obsidian into desired forms, knives, spearheads, and other implements and weapons, while long, slender flakes possessed, for cutting purposes, knife-edges of razor-like keenness. The ancient Mexicans were especially skillful in working it, and were able to spring off blades of bayonet-like cross section, half an inch in breadth by six inches or more in length.

While obsidian corresponding to the various kinds of igneous rocks is known, it usually has a composition similar to that of granite, as may be seen from the analysis of a typical specimen from the Yellowstone Park.

SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	H_2O	FeS_2	
74.7	13.7	1.0	0.6	0.1	0.8	3.9	4.0	0.6	0.4	=99.8

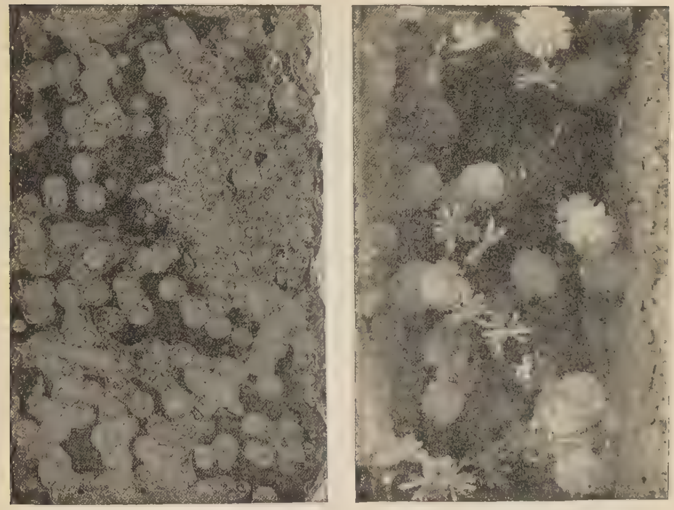
It can be readily shown by calculation that, had this magma crystallized, it would have produced a rock consisting of 35 per cent of quartz, 60 per cent of feldspar, with 5 per cent of other minerals, that is to say, a granite. The specific gravity varies from 2.3 to 2.7, depending on the composition; that of the most common variety is 2.3 to 2.4. The hardness is greater than that of ordinary window glass, which it scratches.

Before the blowpipe a splinter of black obsidian fuses readily, with bubbling, to a vesicular gray or white enamel, which, after the removal of the water, becomes exceedingly infusible. This experiment is very instructive in showing the effect of water in lowering the fusing point of magmas and in increasing their liquidity. The water in the obsidian is not the product of alteration, for it is present in what the microscope reveals as the purest and clearest glass, nor are there cavities to contain it; it appears to be chemically a part of the obsidian, just as is the Na_2O and K_2O.

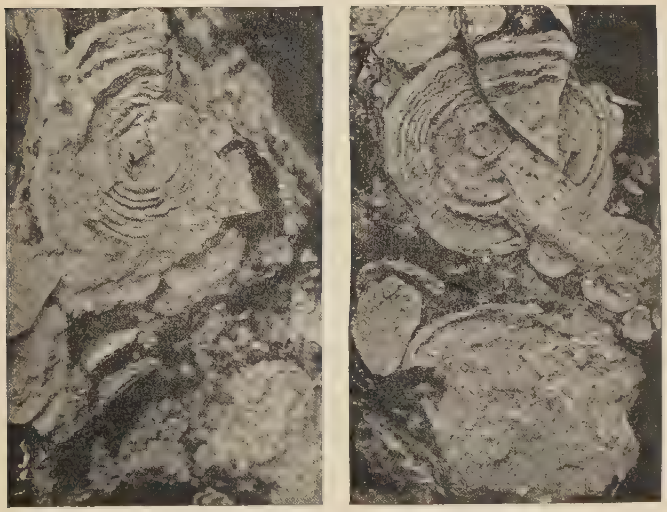
Spherulites. In many obsidians may be seen rounded, sometimes perfectly spherical, bodies of white, gray, or red color, varying in size from those of microscopic dimensions up to those of an egg, or even larger; usually from the size of fine shot to that of peas. If closely examined with a lens, it can generally be seen that they are composed of fibers radiating from a common center; at uniform distances from the center the fibers are likely to change color, or are saturated with a differently colored material, and the body appears as if built of successive concentric shells. These bodies are called *spherulites* and are composed of fibers of feldspar. They are indicative of sudden cooling and a very rapidly induced crystallization, the fibers shooting outward from some center where crystallization commences, and branching as they grow, until checked by the viscosity of the rapidly cooling magma. They should not be confused with phenocrysts which are single, individual crystals. An example is shown in Plate 21. They are sometimes formed by accident in artificial glass, as seen in Plate 21; here the artificial mineral forming them is wollastonite, $CaSiO_3$.

Frequently the spherulites form before the lava has come to rest and are thus drawn out, so that they are dotted along the rock in lines. When in great numbers, and minute, they may coalesce; some streaks of the rock are then composed of them, while other bands are of dark, solid glass, as shown in Plate 22.

PLATE 21.



A. Spherulites in Obsidian. B. Spherulites in Glass.



C. Lithophysæ. D. Lithophysæ.

STRUCTURES IN GLASSY ROCKS.

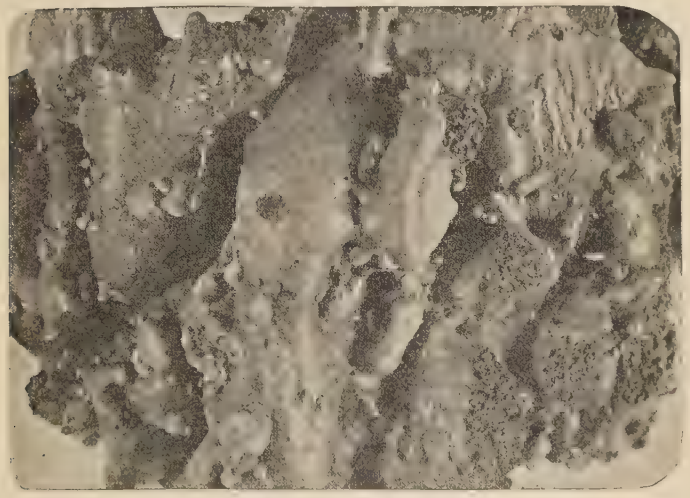
Lithophysæ. Closely connected with the spherulites there occur also in glassy rocks peculiar formations known as lithophysæ (stone bubbles). These consist of a series of concentric shells of crystalline material, somewhat resembling nested watchglasses, which surround a central cavity, and are more or less separated from each other. They consist of adherent crystals, and are very fragile. When exposed by the breaking of the rock they appear much like flowers with concentric layers of petals. They vary in size from very small to several inches in diameter. The walls of the cavities are coated with minute but beautiful crystals of quartz, tridymite, and feldspar, and sometimes fayalite, topaz, garnet, and tourmaline are found in them. Sometimes they are more or less flattened and strung along the flowage planes of the rock. They occur, not only in the pure glassy lavas, but also in lavas that, by more or less crystallization, have assumed megascopically a stony texture and appearance. They are illustrated in Plate 21. Their origin is ascribed to repeated shells of crystallization, with consequent liberation of water vapor, and expansions of the cavities through its influence under high temperature. The formation of topaz and other minerals points to the presence of fluorine and other accompanying gases. Thus the lithophysæ seem to bear a certain analogy to miarolitic cavities in the intrusive rocks, as described elsewhere.

Pitchstone. This may be regarded as merely a variety of obsidian in which the luster, instead of being bright and glassy, is duller, and the rock appears resinous or pitch-like. There is also a chemical difference in that, while the water contained in obsidian is rarely so much as one per cent and may sink to mere traces, pitchstone contains much more, as much as 5 or 6 per cent or even more. It is this which probably influences the luster. Pitchstones are also variable in color, — black, gray, red, brown, and green, and are translucent to transparent on thin edges.

Perlite. This is a peculiar variety of glassy rock which is composed of small spheroids, usually varying in size from

PLATE 22.

A. FLOW STRUCTURE IN GLASSY LAVA.



B. SLAGGY STRUCTURE OF BASALTIC LAVA.

small shot to peas. It is generally of a gray to blue-gray color, rarely red, has a soft, pearly, or wax-like luster and resembles enamel. The spheroids either lie separated in a sort of cement and are round, or they are closely aggregated and polygonal. They tend to have a concentric, shelly structure and are the result of a contraction phenomenon in the cooling glass, which produces a spherical, spiral cracking, as shown in thin sections. Analyses of perlites prove them to have a rather constant percentage of combined water, between 3 and 4 per cent, and there may be a connection between this amount of water and the peculiar method of cracking. To the casual observer they somewhat resemble oölites and pisolites of the concretionary sedimentary rocks. Perlite is produced only by felsitic magmas, especially by those high in silica; it does not occur in basaltic glasses.

Pumice, Scoria, etc. Pumice is highly vesicular glass produced by the extravasation of the water vapor at high temperature, through relief of pressure, as the magma comes to the surface. It is best described as glass froth. Its color is white, gray, yellowish, or brownish, rarely red. It sometimes has a somewhat silky luster. Examined with the lens, it is seen to be composed of a mass of silky glass fibers of a cottony appearance, full of pores, and separated by larger holes like a sponge. If drawn out by flowage the fibers are parallel; otherwise they are interwound. The chemical composition of typical pumice is like that of the highly siliceous obsidian, or in other words, like that of granite. Pumice does not form independent rock masses; it occurs as the upper crust of flows of felsite lava, or in fragments among the explosive material ejected by volcanoes. On account of its light, porous nature, and its content of sealed glass cells, it floats almost indefinitely on water, and the material ejected by volcanoes near or in the sea is borne by currents all over the world, and drifts ashore everywhere. It use as an abrasive and polishing agent, and for toilet purposes, is due to the sharp cutting edges of the thin films and fibers of glass. Nearly all that is used comes from the

Lipari Islands off the coast of Sicily. Other places of occurrence are mentioned later.

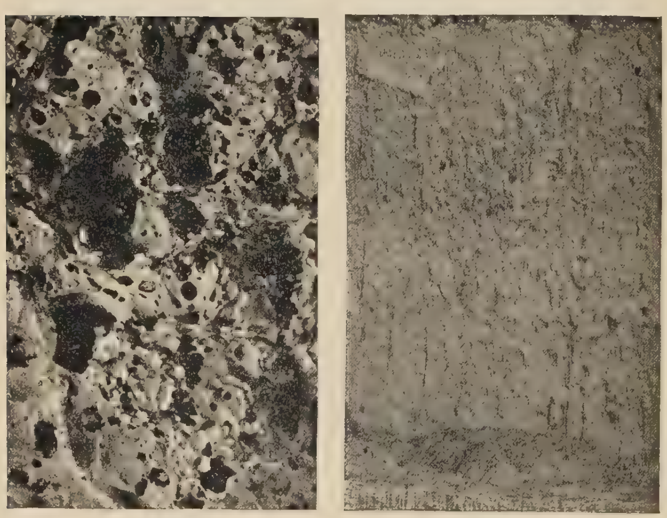
Scoria. While all magmas, whatever their chemical composition, at times and under proper conditions form pumiceous rocks, typical pumice, as stated above, is most characteristic of the felsitic magmas, while basaltic pumices are of local development and of inconsiderable importance. Nevertheless the basaltic magmas develop vesicular forms, through the expansion of gases, as described under basalt. These pass, especially on the upper surface of basalt flows, and in the material thrown out by volcanoes, into more or less glassy, partly stony, dark or reddish, loosely compacted, spongy, cindery, or slag-like modifications known as volcanic scoria. This form is illustrated in Plate 23.

A peculiar modification of what may be considered basaltic pumice occurs in the crater of Kilauea in Hawaii, where drops of lava flying up from the boiling lava lakes pull out thin, hair-like threads of glass after them. These threads, drifted by the wind, collect in tow-like masses, called by the natives "Pele's hair" after the titulary goddess of the islands.

Vitrophyre. Either pitchstone or obsidian may contain embedded crystals or phenocrysts which can be recognized. As in felsite porphyries, the amount may vary widely from cases in which they are rare and widely scattered to those in which the rock is thickly strewn with them. Such porphyries, consisting of a glass base and phenocrysts, are called vitrophyre. Perlite porphyries are known, but are rare. The glassy base of vitrophyre has the properties of the obsidian or pitchstone previously described; it often contains spherulites in addition to the phenocrysts. Feldspar is the mineral most common as phenocrysts; it is generally limpid with a glassy habit; the cleavage distinguishes it from quartz, which may also occur, sometimes alone and sometimes with the feldspar. If phenocrysts of a ferromagnesian mineral are present they are usually biotite, less commonly hornblende, while pyroxene, though known, is rare. The varieties are usually named according to

PLATE 23.

A. VOLCANIC BOMB.



B. SCORIA. C. PUMICE.

the prevailing phenocryst without regard to the character of the groundmass; so we have *quartz vitrophyre, feldspar vitrophyre, quartz-biotite vitrophyre,* etc. The phenocrysts are generally rather small.

The chemical composition of the vitrophyres is similar on the one hand to the felsites and on the other to the pure glasses; they represent an intermediate stage of development, as may be seen from the following table, which shows the relations of all these varieties of extrusive rocks or lavas to one another.

Conditions under which Magma Cooled and Solidified	No Formation of Crystals in the Depths before Extrusion; no Phenocrysts	Crystals Formed in Depth before Extrusion and Brought up by Magma; Phenocrysts
No crystallization of magma on Earth's surface, because of rapid cooling. — Glassy texture.	Pitchstone and Obsidian	Vitrophyre
Crystallization of magma on Earth's surface; slower cooling. — Stony texture.	Felsite	Felsite porphyry

Tachylite. As previously stated, basaltic magmas crystallize easily and rarely form glass, or only in relatively small volume. Basaltic glass is, however, seen occasionally as a thin marginal facies or selvage in dikes, on lava flows, or among the products of basalt-yielding volcanoes, like those in Hawaii. It is known by the name of *tachylite.*

Occurrence of Glassy Rocks. The glasses are found in those regions that are, or have been in the past, scenes of volcanic activity. While obsidian and pitchstone occur as independent flows and masses near volcanic vents, the glassy rocks in general form only the upper surface of lava sheets, which become crystalline as they are penetrated downward. Glassy rocks are also found, especially in pumiceous forms, in the fragmental material ejected by volcanoes. To attempt to name all the different occurrences would be impracticable, but it may be mentioned that obsidian in large masses is found in the Yellowstone Park and is known for its beautiful spherulites and lithophysæ; at Mono Lake in California; Glass Butte, Oregon; White Mountains, Utah; Tewan Mountains, New Mexico; and various other places in the United States. It is also found in Mexico, Iceland, Lipari Islands, Italy, Hungary, New Zealand, Transcaucasia, etc. Pitchstone occurs in Colorado near Georgetown and at Silver Cliff; well-known localities are on the Island of Arran off the west coast of Scotland, in Ireland, and at Meissen and Tharandt near Dresden, Germany. Perlites and pumice are also found in the Yellowstone Park, as well as in Hungary, Italy, Iceland, Japan, etc. Basaltic glasses occur on the west coast of Scotland, in Iceland, and more especially in the Hawaiian Islands.

Alteration of Glassy Rocks. It has been found by microscopic and field study that ancient lavas, in a variety of places, were once glassy, though not so at present. It appears that when the natural glasses are exposed to the various agencies which tend to alter rocks, such as pressure, heat, action of water, etc., they undergo a slow change, and the glass is converted into an intimate mixture of excessively fine particles of quartz and feldspar, and loses entirely its vitreous character. It then assumes the stony texture and becomes an aphanitic felsite. This change is called *devitrification.* While the former glassy condition of many felsites cannot be proved, even microscopically, it may often be suspected from the presence in them of chains of spherulites, flow structures, and lithophysæ, which may be seen megascopically, and give strong hints of their former character. Ancient altered lavas of this kind have been described from the coast of Maine; from South Mountain, Pennsylvania; from Wisconsin; from Sweden and other places.

Fragmental Volcanic Rocks

Origin. The fragmental igneous rocks represent the material thrown out by volcanoes during periods of explosive activity. The explosive action is due to vapors, chiefly that of water, which is contained under pressure in the magma, and as the latter rises to the surface and the pressure is relieved, departs with violence. While the major part is passing off in great volumes, which rush upward and carry the solid or liquid materials to great heights, a minor part is also expanding in the liquid, converting it into cellular vesicular forms. Consequently the solid particles as they fall are commonly found to be of spongy consistency, but mixed with them are often seen compact pieces of lava and other rocks, parts of the solid lava crust formed by cooling after a previous eruption, mingled with fragments torn from the rock walls of the conduit. As the lava continues rising, the greater volume of the gases may pass off, the explosive activity ceases, and the projection of material may be succeeded by quiet outflows of liquid rock. Hence it is very common to find the beds of fragmental material interspersed with layers of compact lava, felsite or basalt.

In this connection it should also be mentioned that the chemical composition of the magma plays a considerable part in explosive activity. Those magmas that correspond to felsite and are high in silica, are, as has been mentioned, very viscous at temperatures at which those low in silica, such as the basalt magmas, which are rich in iron, magnesia, and lime, are still relatively very liquid. From the siliceous magmas, on account of their thick viscous condition, the vapors escape with difficulty, and with explosive violence; from the basaltic magmas they pass off readily and easily without explosive activity. While there are many exceptions to this, it may be accepted as a general rule, and we therefore find that vents yielding felsite lavas generally build high and steep cones, composed chiefly of fragmental materials, while basaltic ones are built up largely of liquid outflows and are therefore low and broad. Many volcanoes, like Vesuvius, are of intermediate character; in such volcanoes explosion and projection of material alternate with flows of lava, and the cone is consequently of composite character.

Classification. The particles of magma, driven into the atmosphere and solidified, and the pieces of rock are of all dimensions from the finest dust, which may float for years, to huge masses weighing several hundred pounds. By general usage, for the sake of convenience, the following sizes are roughly distinguished: pieces the size of an apple or larger are called *bombs;* those the size of a nut are termed *lapilli;* those the size of small peas or shot, *ashes;* the finest are known as *volcanic dust.* Sometimes the bombs, lapilli, etc., are sharply angular and sometimes smoothly rounded off — a form caused by the grinding and attrition of the pieces upon one another in the upward rush from the volcanic throat. They should be distinguished from bombs which have been rounded afterwards by the action of running water. The larger bombs sometimes present a sub-angular appearance, are porous, and have their surface penetrated by cracks as shown in Plate 23. Such have been called bread-crust bombs. The ashes and lapilli, which usually make up the greater part of the material, are frequently spoken of as *volcanic cinders,* and cones composed of them are called cinder cones.

In a sense, of course, this loose material may be estimated as a rock formation; so far as the individual pieces are concerned, they are to be considered merely as fragments of the various kinds of rocks treated in the foregoing pages, to be named and described as there set forth.

But in process of time great accumulations of such material may be spread over wide tracts of country, covering up existing rock formations. The heavier and coarser particles fall first, then the finer, giving a gradation from top to bottom and, as successive outbursts occur, there is produced in this way a rough bedding. By its own weight as it accumulates, aided by the action of percolating water which may carry and deposit substances in solution, it gradually becomes compacted into a more or less firm mass, having a certain individuality as a kind of rock and deserving of special treatment. When the rock is composed entirely of the finer particles, dust and ash, it is called *volcanic tuff;* when this is mixed with the coarser bombs and lapilli it is termed *volcanic breccia*, from the broken, angular character of the embedded fragments.

Volcanic Tuff. This is generally a fine-grained rock, light in weight, and often of a chalky consistency, sometimes aphanitic, compact, and breaking into small chips. The color is usually light, white, pink, pale-brown, gray or yellow, sometimes passing into darker shades. The more compact varieties may be easily mistaken for felsite lavas; it is possible that some of them cannot be distinguished from felsite megascopically, but generally attentive examination with a good lens will reveal angular particles of quartz, feldspar, and often of other minerals in them, and possibly small fragments of other rocks. When not too compact they have a rough feel and when strongly rubbed between the fingers yield a gritty dust, unlike the smoothness of pure clay or chalk, owing to the hard, angular character of the dust particles. Sometimes such tuffs contain fossil remains of vegetation, when they have fallen upon land surfaces covered with it, and carbonaceous remains of stems, twigs, or leaf imprints may be found in them. If the material has fallen into water the tuff may be rich in various kinds of fossils, such as marine organisms, possibly of great perfection of form, and for the same reason it may be well stratified. All of these varied characters, including the mode of occurrence and relation to other rocks, must be taken into account in judging the nature of the deposit.

Volcanic Breccia. This has a base or cement of tuff, more or less completely filled with lapilli of angular shapes, and these are often mingled with larger bombs and masses which are likely to be rounded. Interspersed with these are likely to be fragments of other rocks, such as limestones, shales, sandstones, and massive crystalline rocks, granite, gneiss, schist, etc., pieces of the basement through which the conduit has been drilled. Even when these rocks have been greatly indurated by contact metamorphism, or other agencies, they still reveal, by differences of color and texture on a freshly broken face, the angular shapes of the fragments and their composite character. When not too indurated they are apt to erode very unevenly; the finer cement, being less resistant, washes away first, leaving the contained masses projecting, and in this way, along the edges of cliffs, strange and weirdly shaped figures of erosion are produced, called " hoodoos " in the Rocky Mountain region. The color of these breccias is variable, browns, reds, and chocolate being common, along with lighter tones, depending partly on the state of oxidation of the iron-bearing compounds they contain, and partly on the nature of the magma, whether felsitic, which tends to lighter colors, or basaltic, which produces darker ones.

Occurrence of Tuffs and Breccias. These rocks are of wide distribution, being found in all regions where volcanic activity has taken place; their presence indeed is the best confirmation in many regions of such activity in the past. In places where volcanism is still active, or has only recently ceased, they are represented by the still uncompacted material, but no definite line can be drawn between the different conditions of consolidation.

In the eastern United States, tuffs and breccias have been found in several localities in Maine; near Boston; and at South Mountain, Penn. They occur also, to a limited extent, with the Triassic eruptives of the Connecticut Valley. Further research will probably reveal other localities, but they are neither common nor conspicuous rocks, being limited in volume and so greatly changed in character by various agencies that in many places their true character is recognized with difficulty. They probably had once a much greater extension, but erosion has carried away the greater part of them during the vast period of time which has elapsed since volcanic activity was displayed.

In western America, however, the case is very different; in the various ranges of the Rocky Mountains, in the Coast and Cascade Ranges, and in fact over most of western North America, these are common rocks; and in many places in

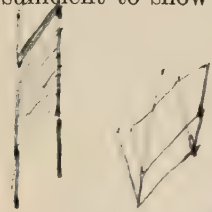
PLATE 24.

BEDDED VOLCANIC BRECCIAS, TABLE MOUNTAIN, ABSAROKA RANGE, WYOMING.

(U. S. Geological Survey.)

Colorado, Wyoming, and Montana they occur in immense deposits, often forming an important factor in building up the bulk of the mountain masses. They are especially well displayed in western Wyoming, in the region of the Yellowstone Park, where the serried peaks of the Absaroka Range are mostly carved out of tuffs and breccias aggregating thousands of feet in depth, thus testifying to the enormous volcanic energy which this region formerly displayed. A section cut into them by erosion, exhibiting their rough bedding, is shown in Plate 24. In this region they are frequently interbedded with flows of lava.

In Europe tuffs and breccias have a wide extension. They occur in many places in the British Islands, as in the Lake district in northern England, and associated with the volcanic rocks of the Old Red sandstone and Carboniferous of Scotland. They are often interbedded with sedimentary rocks and are frequently so altered by metamorphic processes as to be recognized only by careful petrographic research, having been changed into slates, etc. Such altered tuffs form a part of the so-called "hälleflintas" in Sweden or the "porphyroids" of Continental geologists. Tuffs and breccias occur in many places in Germany, France, Italy, etc. The mention of these localities is sufficient to show their wide extension and importance.



Start here for [illegible]

1. unconsolidated { 1. sediments / soluble salts.

2. weathering { 1. disintegration / 2. decomposition

3. previously existing rocks.

CHAPTER VIII

ORIGIN AND CLASSIFICATION OF SEDIMENTARY ROCKS

The sedimentary rocks consist of material that has already formed a part of pre-existent rocks, and that has been moved from its former position, deposited by the action of water, of the atmosphere, or of glacial ice, and subsequently converted into rock (lithified). The action of water is by far the most prominent and important, especially with respect to the volume of the masses involved, and the frequency of their occurrence, and accordingly when sedimentary rocks are mentioned such water-formed or aqueous rocks are always meant, unless it is otherwise stated. In contradistinction to them, the material that has been moved and deposited by the action of the atmosphere forms the class known as *æolian rocks*, one of far less importance, and the ice-laid rocks are still less important. From what has been said, it is clear that the sedimentary rocks are *secondary* ones in that their material in some form or other has been derived from already existent rocks. An exception to this would be found in beds of volcanic ashes which have been deposited from the atmosphere, and which have been described by preference under the igneous rocks. But in general the statement that the material of the sedimentary rocks is secondary holds true; this material has been derived from former rocks of all classes — igneous, metamorphic, and sedimentary — and, in the earliest sediments, from the Earth's original crust, if such ever existed.

The rocks that have been formed in water may be divided into two main groups, according to the manner in which the material has been deposited; they consist either of substances mechanically held in suspension and then directly dropped, or of substances that have been in solution, and through chemical agencies, either of organic life or otherwise, have been rendered insoluble, and therefore deposited. The first we may call *mechanical,* the second *chemical* sediments. Yet even between these, as we shall see later, it is difficult to draw a definite line. It is well to remark here that the distinction between a sediment and its lithified equivalent (a rock) is very loosely drawn in current geological usage. We have then the following classes to deal with:

Aqueous rocks;	water-laid	mechanical. chemical.
Æolian rocks;	wind-laid	mechanical.
Glacial rocks;	ice-laid	mechanical.

Decay of Rocks; Formation of Soil. When firm and even close-grained rocks are exposed to the action of the atmosphere, they gradually decay and are turned into soil. This is brought about by a variety of agencies. All rock masses are penetrated in various directions by cracks and fissures called *joints;* these are both great and small, and in addition the individual mineral grains contain cleavage and other cracks. Thus water is able to permeate the rock masses thoroughly, and in cold regions where alternate thawing and freezing goes on, the expansion of the water in turning to ice keeps on splitting and crumbling the rocks until on the surface they are reduced to a mass of débris. The expansion and contraction of rocks in hot countries and in arid regions, under great daily and yearly changes of temperature, accomplishes the same thing more slowly. The expansion of the growing roots of trees and plants tends to the same end. By such processes there is a constant tendency for the rock masses to be broken up, *mechanically,* into smaller and smaller fragments. In the meantime the substances dissolved in the water, such as air, acids from decaying vegetation, and especially carbonic acid gas, are acting *chemically* upon the rock minerals, converting the silicates, oxides, and sulphides into other forms, such as carbonates, hydrated silicates, hydroxides, sulphates, etc. Much material goes into solution, is leached out, and is carried by running water into lakes and the ocean, where it concentrates, and where we must again consider it under the formation of the chemically precipitated sediments. Some minerals, such as quartz, are not attacked to any appreciable extent, or but very slowly, under ordinary circumstances, and these remain to form the chief part of the rock débris. It is for this reason that silicates, and especially quartz, play the chief mineral rôle in the sedimentary rocks formed by mechanical processes. This débris of broken, crumbled, and altered rock, which constitutes a detritus, has been called by various names, and the finer upper portion in which vegetation grows is the soil. Under this latter name, for convenience, we may consider all of it. The gradual change from rock below to soil above is illustrated in Plate 17.

Movement of Soil. The surface of the land in general is covered by a mantle of soil resting on the rocky crust of the Earth. The latter, which is popularly known as the " country rock," here and there in ledges, precipices, and the craggy tops of hills and mountains, projects through this covering. By the action of running water, aided by gravity, this crumbled rock and soil mantle, which is apparently at rest, is, geologically considered, actually kept in motion, and is continually being urged downward into the sea, its ultimate goal, Plate 25. On steep slopes it goes more rapidly, in valleys more slowly; in level plains, like water in a lake, it is temporarily impounded. Its rate of motion varies continually from time to time and from place to place. Its movement in mass is, of course, very slow; when it is suspended in running water, its rate of movement is that of the water which carries it; when it is resting on the stream bottom, the rate varies according to circumstances. Thus the land waste is ever being carried away and renewed by the destruction of the rocks. The greater part is carried into the sea, but a considerable part is deposited in inland lakes and seas, and on the lower plains and deltas of great rivers, which from time to time are heavily flooded. It is this material which forms the sedimentary rocks of mechanical deposition.

PLATE 25.

TALUS CONES, SHOWING MOVEMENT OF ROCK WASTE, HEAD OF STINKING WATER RIVER, WYOMING.

(U. S. Geological Survey.)

Size in

Gradation of Material. The detritus of the land consists of material of very variable sizes. In northern countries over which glaciers have passed this is particularly likely to be true, as rock masses showing great extremes in dimensions are moved and mingled by the glaciers. When such material is moved by running water it becomes sorted and graded, according to the strength of the current, into masses consisting approximately of equal-sized particles. When the particles are larger than peas the material is called *gravel* and the individual pieces are termed *pebbles;* large, loose pieces of rock from the size of a small melon up are spoken of as *boulders.* Pieces smaller than peas, which form a non-cohering mass when wet with water, are termed *sand;* while the finest particles which are readily lifted and transported by movements of the atmosphere are known as *dust,* and these when wet and then dried generally cohere into solid material. All these grade into one another. The following table shows a more accurate division according to size.

Name of Material	Diameter in Millimeters
Fine Gravel	2–1
Coarse Sand	1–0.5
Medium Sand	0.5–0.25
Fine Sand	0.25–0.1
Very fine Sand	0.1–0.05 200 mesh screen.
Silt	0.05–0.01
Fine Silt	0.01–0.005
Clay	0.005–0.0001

25.4 Mil. = one inch.

Thus, roughly speaking, the material may be classified into, (*a*) gravel, (*b*) sand, (*c*) mud, clay, or silt. Since this division is made the basis of classification of the mechanically formed sedimentary rocks, each kind of material may be examined somewhat more in detail.

Gravel. The pebbles which compose a gravel are pieces of individual rocks and, like them, are generally made up of grains of different kinds of minerals. Some pebbles are composed of only one mineral, and of these quartz is by far the most common. Such quartz pebbles may be fragments derived from quartzite strata, from a quartz vein, or from large quartz crystals from some granite-pegmatite dike. Such coarse granites or pegmatites may furnish pebbles consisting of other single minerals, especially feldspar.

The form and appearance of pebbles depend on the conditions to which they have been exposed. Those that have suffered considerable transportation in the bed of streams, or have been rolled on the shores of lakes and of the sea, are, as is well known, rounded, and become ovoid to spherical. They are likely to have a very smooth surface with a characteristic faintly dimpled, slightly dented, or inverted shagreen appearance, caused by their repeated collisions during movement. This is best seen on a pebble of a hard homogeneous substance, as in one of quartz. If composite in nature they are often pitted by the decay and removal of softer or more easily altered particles.

The degree of rounding shown by pebbles depends on the distance and length of time they have been transported and on the hardness of the material. Sedimentary rocks, as will be shown, are sometimes composed of pebble-sized fragments that have suffered very little movement and still retain their original rough, angular character.

Pebbles and boulders that have been transported by glaciers are sometimes seen in sedimentary rocks. These have characteristic sub-angular forms, with faces ground upon them, which are polished and scratched by parallel and crossing grooves or scratches. Pebbles, partly buried in the sand of the seashore and of deserts, are also often sub-angular and faceted, the faces being ground by the sand drifting past them, but these lack the scratches.

Pebbles buried in the soil often show fern-like or moss-like markings or dendrites upon them, or are sometimes covered with a shiny skin of dark color. This comes from manganese or iron oxides that are deposited by water.

Sand. Strictly defined, sand means particles of a certain size, as mentioned above, and has no reference to their composition: thus we have quartz sand, coral sand, volcanic sand, etc. It happens, however, that by far the greater part of the sands are composed of particles of quartz, and some are exclusively made up of it. For this reason, when the term sand is used without qualification, quartz sand is always meant.

The composition of ordinary sand is quite variable, depending on the locality. In addition to the dominant quartz grains, those of many other minerals are present as subordinate constituents, depending on the rocks of the region. Feldspar, garnet, and magnetite are very common. Various silicates, such as hornblende, pyroxene, tourmaline, etc., are likely to occur. Some grains may be made of pieces of very fine-grained rocks of composite character. Twenty-three different kinds of minerals were found in the dune sands of Holland by Retgers, though the actual amount of these minerals other than the quartz was a fraction of one per cent.

Like pebbles, the sand grains are more or less rounded, depending on the amount of transport. In some rather coarse sea sands they are almost all spherical. Below a certain degree of fineness the grains do not become more rounded by attrition in water among themselves; this is due to the fact that the capillary film of water covering them acts as a buffer and prevents them from coming in contact when they collide; in the larger grains it is not able to do this. In wind-blown sands, especially those of the desert, the quartz grains become rounded to minute perfect spheres having the so-called ground glass surfaces.

Mud, Silt, and Clay. These are the finest material of the land waste. As sedimentary deposits they are characteristically found off shore, or in sheltered bays and sounds, where the slow movement of the water does not permit the transport of the heavier sand and gravel, and as the material forming the lower flood plains and deltas of great rivers. On account of their minute size the particles are not likely to be rounded, but under the microscope show angular forms. Like the sands they may be composed of a great variety of minerals, kaolin, mica, quartz, feldspar, etc.; but just as quartz is the characteristic mineral of the sands, so is kaolin that of muds and clays. As shown elsewhere, the decay of the feldspars of the rocks produces kaolin or clay, while the quartz grains are unaltered; the clay particles are excessively fine and light, while the quartz ones are mostly larger and heavier. Because of this there tends to be a separation of the two by moving water; as the current slackens the quartz is deposited first, forming sand, while the lighter clays are carried beyond and settle in still water. Fine flakes of white mica often accompany them.

In fresh water a portion of most clays, consisting of the very finest and lightest particles, will remain in suspension almost indefinitely. Turbid water of this kind acts much as if it were a solution of clay in water; if salts be added to it, or if it be mixed with sea water, the clay then curdles into lumps or flocculates and is quickly deposited, leaving the liquid clear. This behavior is analogous to that of salts in solution, and it has an important bearing on the deposition of material carried into the sea, and on the formation of certain kinds of rocks.

Muds or clays are characterized according to the predominance of certain constituents; thus some are calcareous, containing more or less calcium carbonate, and are often called *marls;* some contain a good deal of fine quartz and are spoken of as siliceous; others are rich in deposited iron oxides and are ferruginous clays or ochers; while in many these constituents are present in minimum amount, or are wanting, and these are common clays or argillaceous deposits. Such mixed forms are transitional to the chemically deposited rocks described later.

Dissolved Material. The waste of the land includes not only the material mechanically transported by water, but also that which is taken into solution and ultimately carried into the sea. A rough estimate of the dissolved material removed from the continents places it at 5,000,000,000 tons per annum. It is an important fraction of the whole amount removed, compared with the mechanical sediments. It varies greatly in different rivers, depending on the composition of the rocks forming their basins. It is inferred that through the concentration of this material in solution during past ages the salts now in the ocean have been produced. From these salts have been formed those sedimentary rocks, whose material through chemical agencies, either of organic life or otherwise, has been redeposited from solution. They include the important class of carbonates, limestones, dolomites, etc., and the less important sulphates and chlorides, such as gypsum and rock salt.

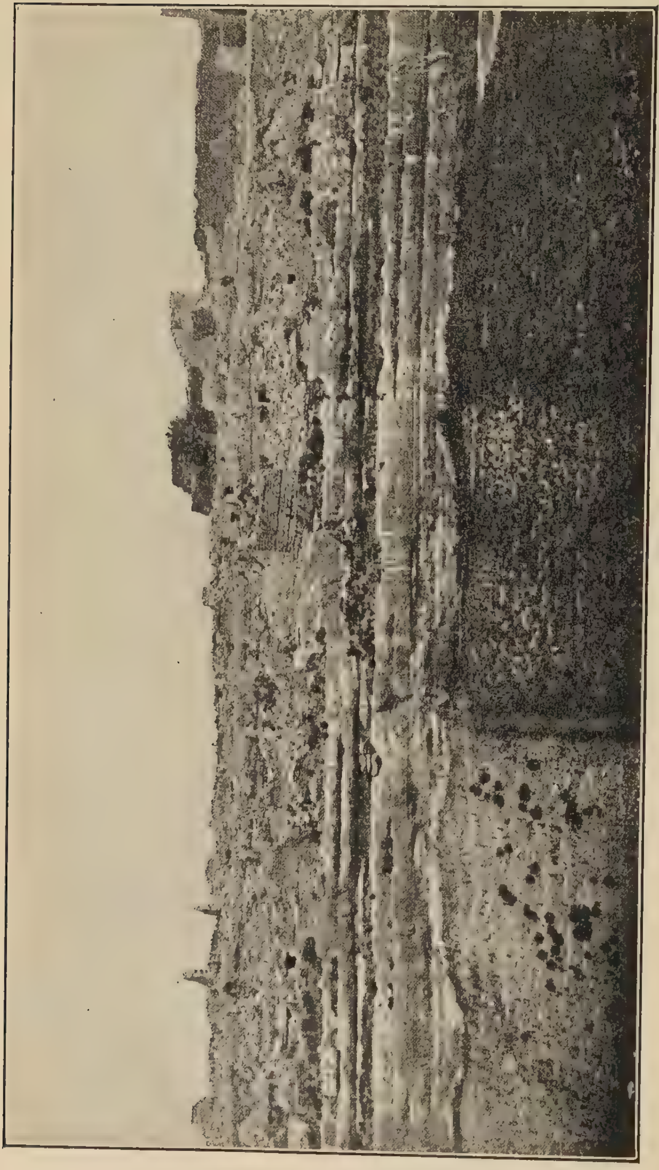
It is probable that the carbonates of calcium, magnesium, and alkalies were all originally derived from silicates of these metals. Water containing carbon dioxide has converted the silicates into carbonates, as illustrated under the decomposition of feldspar, and has then dissolved and carried them into the sea. The sulphates have been formed by the oxidation of sulphides in the original rocks and the union of the sulphuric acid with the stronger, more soluble, alkaline bases. The chlorides have in part been derived from minerals of the original rocks and, perhaps, made in part by volcanic emissions from deep-seated magmas within the Earth.

Structure of the Sedimentary Rocks. The sedimentary rocks, as geological masses, differ greatly from the igneous ones in that they form widely extended, relatively thin bodies, making part of a coating or mantle upon the Earth's outer surface; they never prolong themselves by extension into the depths, as the latter always do. It is thus their horizontal, as contrasted with their vertical extension, that gives them importance as geological masses. The most characteristic feature about their structure is that they are *stratified*. This means that they consist of layers, varying in material, texture, and color, and in thickness. If undisturbed by geological events more recent than their formation, these layers are in general horizontally disposed one upon another. This is illustrated in Plate 26. It is due to the fact that the mechanical sediments have been deposited by currents of water in lakes and seas and on the flood plains of rivers, and these currents, acting on diverse material and continually varying in strength, have assorted the sediments and deposited them in strata. For further consideration of this subject, information should be sought in any of the numerous manuals of geology; but it may be stated as a general law that sedimentary deposits are always stratified and that, conversely, perfect stratification, resulting from an assortment of particles, is regarded as a proof of deposit in water.

Volcanic ash deposits are commonly rudely and sometimes well stratified; the heavier of the particles projected upward fall first and are succeeded by smaller, lighter ones. Repetitions of the process make individualized beds and thus a rude stratification (see Plate 24), while the lighter dust may be deposited by air currents much as if in water.

For stratification, variation, both in conditions and in the size of the particles, is necessary; during a period in which uniformity prevails in

PLATE 26.



STRATIFIED BEDS OF LIMESTONE, CRIMEA, RUSSIA.

either, stratification will be wanting. Thus æolian deposits, which consist of the finest sands and dust driven by the wind, are often so uniform with respect to the size of the particles in any one area that no stratification, or but very little, is produced. In the same way deposits of calcium carbonate, as limestone and chalk, may take place in the open ocean under such uniform conditions and with such uniform size of particles that beds of these rocks, perhaps a hundred feet in thickness or more, are quite structureless and devoid of apparent stratification throughout that extent.

Mere parallelism of layers in a rock is not in itself a mark of stratification and therefore a proof that the rock exhibiting it is of sedimentary origin. Its mineral composition, texture, and relation to the accompanying rock masses, and to the general geology of the region, must also be taken into consideration. For example, flowing lava may draw out portions of itself that are of unlike character into a series of thin superimposed sheets, as illustrated in Plate 22. Such lavas when fresh are easily recognizable, but buried in the midst of sedimentary deposits and changed in appearance by geologic ages of exposure to various agencies, they may be confused with the accompanying stratified rocks. Again, very perfect parallelism of layers and structure may be induced in all kinds of rocks by the shearing and metamorphism that accompany movements of the Earth's crust and mountain building. These parallel structures of metamorphic origin may superficially simulate stratification quite perfectly, but consideration of the points mentioned above is generally sufficient to show the difference between them. Many serious errors in understanding the real origin of the rocks of different places and their geology have occurred in the past through failure to appreciate these facts properly.

The individual layers of stratified rocks, which are uniform in texture, color, and composition, may vary from the thinness of paper to a hundred feet or more in thickness. Usually, it will be observed that a certain layer, which has a general similarity of character and composition that serves to distinguish it clearly from others above and below, is made up of much smaller subdivisions whose differences from one another are not very marked. The larger division is usually known as a *layer* or *bed*, the smaller ones are termed *laminæ*. The main differences between laminæ are generally in coloration; those between beds, in texture and composition, as shown in Plate 33. As explained above, under uniform conditions *laminæ* may be wanting in a particular bed. The general homogeneity of a bed is shown by its particular hardness and appearance, its individual method of cracking or jointing, and the way in which it is affected by erosion, as compared with the beds above and below it. A collection of beds lying concordantly one above another, and deposited during a given geological period of time, is called a *formation*.

Texture of Sedimentary Rocks. This depends upon the relative size of the particles, which determines the fineness or coarseness of grain, upon their shape, and upon the amount and character of the cement, which determines the firmness or friability of the rock. The *size of grain* varies within wide bounds, but as explained previously under gradation of material, this in itself determines largely the kind of rock. Thus conglomerates are of necessity coarse-grained rocks; sandstones, medium-grained ones; and shales, fine-grained or compact. Still, within the limits of each class there is variation in this respect and we are accustomed to speak of fine, medium, and coarse-grained sandstones; a medium grain in this rock is about that of ordinary loaf sugar.

The *shape* of the component grains, when these are megascopically visible, depends on the amount of transport which they have suffered, as explained under gravel. Usually they are more or less rounded or ovoid, but sometimes quite angular. The latter is more likely to be the case as the size of grain increases. Sometimes this broken, angular character of the particles can be distinctly seen in medium-grained sandstones and arkoses by close observation with a good lens. It shows the rock to have a distinctly *clastic* nature. In coarser rocks and in conglomerates it becomes very striking, and such rocks are called *breccias* and are said to have a breccia structure. This is illustrated in Plate 32. Such breccias are not to be confused, however, with volcanic breccias, as described on page 279.

The *cement* is that which binds the particles of sedimentary rocks together and converts them from loose material into firm rock. Various substances act in this capacity, according to circumstances; sometimes the cementing material is carried into the rock from outside sources in solution and deposited in its pores, sometimes part of the sediment itself goes into solution and is redeposited, and sometimes it consists of fine material mechanically enclosed with the sediment. In the first and second instances silica and calcium carbonate are common binding materials; in the third, clay or clay-like substances perform this function. Iron oxide, probably according to the second method, is also a not uncommon cement in the form of hematite, or göthite, or limonite. The fine deposits of mud and clay appear to be able to consolidate into firm rocks, under the pressure of superincumbent masses, without the presence of a perceptible cement, though it is sometimes present.

The firmness of the rock depends, then, in part on the amount of cement and its quality, and in part on the pressure to which it has been subjected. As a result, all degrees of firmness are shown by sedimentary rocks; some are very hard, firm, and compact, breaking like igneous rocks under the hammer and susceptible of a polish, like some limestones and sandstones; while others are so loose, incoherent, and friable that they may be readily rubbed to powder under the fingers, as with chalks and some sandstones. All gradations may be found between these extremes.

Color of Sedimentary Rocks. This depends partly on the color of the constituent mineral grains or particles, and partly on included substances which act as a pigment. The most common minerals that form the sedimentary rocks are quartz, kaolin, feldspar, calcite, and dolomite; these are naturally white or colorless substances, though they sometimes display exotic coloration, and rocks composed purely of them, without included pigment, are white, as illustrated by certain sandstones, clays, and chalk. Generally more or less pigment is present, the common pigments being the oxides of iron and carbonaceous matter. The iron occurs in the form of ferric oxides, or hydrated oxides, as hematite, or probably hydrohematite (turgite), which give red to red-brown colors, or as limonite, or göthite, which produce yellow to yellowish-brown tones. Carbonaceous matter or finely divided carbon is black, and this is the color of the rock that contains an excess of such matter; as the amount lessens, dark grays are formed, and so on into pale grays. If both organic carbonaceous matter and iron oxides are present in the rock, the former exerts a controlling power over the coloring capacity of the latter in this way: in the presence of organic matter, especially when it is decaying, iron is reduced from the ferric to the ferrous condition, changing from ferric oxide to ferrous carbonate; and as ferrous compounds are colorless or light-colored the rock has the tones of color produced by the carbonaceous pigment. If such rocks are exposed to weathering and the carbonaceous material destroyed, the iron is reoxidized and the red and yellow colors show themselves. This is illustrated in the outcrops and on the joint faces of many black slates which weather red or yellow. On the other hand, if the rocks are devoid of iron, when the organic pigment bleaches out they become white or very light in color. Again, if solutions containing organic matter leach through the rocks, the iron oxide is not only changed into the ferrous condition, but when reduced to this state, or if in it originally, goes into solution also and is carried out, the rocks thus becoming light or colorless.

The most common colors, then, for the sedimentary rocks are white to light gray, to dark gray and black, or from white to pink into red, to dark red and red-brown, or from pale yellow to buff, to yellow-brown. The reds and yellows are often seen commingled in the same rock mass or layer, according to the varying iron hydroxides. In the conglomerates and coarse arkose sandstones, these colors may be modified by those of the fragments of the unchanged original rocks that they contain.

Chemically formed Rocks. These rocks are formed when material that has been in solution becomes insoluble by reason of some agency, and is precipitated. The chief agencies involved are concentration of the solutions and organic life. Animals living in water, chiefly in the sea, secrete inorganic material in the production of their hard parts, either skeletons to stiffen them, or shells as defensive armor for their soft organisms. As the animals die their hard parts collect as deposits. The chief substances secreted are calcium carbonate, $CaCO_3$, and silica, SiO_2, the former being much the more abundant and important. Examples are seen in the formation of reefs and islands by corals, and in the shell-banks made by mollusks. Vegetable organisms also, under certain conditions, secrete silica, and give rise to deposits of that substance.

The deposits produced by concentration occur when bodies of sea-water are isolated from the ocean by geologic processes and become so concentrated by evaporation that they are no longer able to retain the salts in solution. These are then deposited in the order of their solubility. Gypsum and anhydrite, sulphates of calcium, and common salt, sodium chloride, are the most important substances deposited in this way. The same result occurs in lakes and inland seas in arid regions, which have no outlet and in which there is a steady concentration of material in solution, brought into them by inflowing streams. Carbonates, sulphates, and chlorides are the main salts deposited. In a somewhat similar manner, when water passing through the rocks becomes mineralized by taking substances into solution, and then attains the outer air, as in springs, these substances are deposited. With respect to the masses involved, such deposits are of minor importance, geologically speaking, and are illustrated by the deposits of calcium carbonate around springs, and in caves, and of silica around geysers and hot-springs in volcanic regions. More important deposits are those formed where water, in the presence of organic matter, has leached iron oxide from the rocks and soils and, carrying it in solution into swamps and shallow waters, has there deposited it, either in the form of ferrous carbonate (siderite), if there is excess of organic matter present, or in the reoxidized form of ferric hydroxide (limonite) if organic matter is wanting. By this means widely extended beds of iron ore, which are of great technical value and importance, have been formed.

Circulation of Material. Geological science is not yet in a position to make definite statements concerning the origin of the material of the earliest-formed sediments upon the Earth. We know that, wherever upon the continents the deepest erosion has occurred, exposing the basement upon which the visibly earliest sediments have been deposited, this basement is of igneous rock or of apparently igneous rock which has been metamorphosed, and the sediments are such as could have been derived from its erosion and weathering. Whatever the nature of the original sediments was, it is evident that any later ones could have come only from the following sources: (1) from the original sediments after they had been elevated to form land, and had therefore been subjected to erosion; (2) from such areas of the original surface as had remained uncovered by the first sediments and hence were undergoing continued erosion; and (3) from any igneous rocks that had been intruded into rocks of either of the two foregoing categories. This condition of affairs has continued to the present time; sediments have been laid down, and then elevated to form land, sometimes being greatly metamorphosed in the process and sometimes not, and these by their erosion have in turn yielded fresh sediments, and so on. Thus there has been a circulation of material, with changes of conditions to affect the minerals at each stage, and only the most resistant, such as quartz, have been able to undergo the process without change. One stage is a downward course from land to sea; the return journey is the ascension of the land from the sea. The silicate minerals, which chiefly form the mechanical sediments, have performed the downward journey in suspension; the carbonate minerals, on the other hand, have made it mainly in solution. This means that sandstone, for example, on erosion is mostly carried away mechanically, while limestone, which consists mainly or entirely of calcium carbonate, disappears mostly by going into solution, although, at the beginning of erosive work upon it, it may be largely mechanical processes that break down the rock. Some mechanical sediments consisting of calcium carbonate occur, though not relatively of great importance, and these are described under limestone, along with certain deposits of calcium carbonate formed on land by evaporation, which may be regarded as temporary stoppages of the material in solution on its way to the sea, and which are illustrated by the formation of travertine around springs and in caves.

Minerals of the Sedimentary Rocks. From what has been said in the foregoing pages, it is evident that the minerals of the sedimentary rocks consist of those which compose the igneous ones and which have been able to endure without change the various conditions to which they have been subjected, as well as the new ones formed by weathering and erosion. The finer the material and the longer the time of its transport has been, the more thoroughly it will be changed into new mineral combinations. Hence quartz and feldspar are important in the coarser-grained rocks, quartz, kaolin, and mica in the finer-grained ones; while calcite, dolomite, siderite, limonite, and gypsum represent minerals of the chemical deposits. In the fine-grained and aphanitic sedimentary rocks formed of silts, muds, and clays, the particles are so fine that from the megascopic point of view the mineral composition is an element of little value in determining and classifying the rock, compared with its color, texture, structure, hardness, and other qualities.

Chemical Relationships. The chemical and mineral composition of sedimentary rocks is not dependent on definite laws, as that of the igneous rocks evidently is. There are no rules governing the associations of minerals, since these have been brought together by chance, depending mostly on specific gravity, and on size of grain in the assortment. The chemical composition has not in consequence as much significance as it has in igneous rocks. Analyses of a few of the more important types are given in the following descriptive portion, since these may be useful in several ways.

Classification of Sedimentary Rocks. Two systems of classification are used for the sedimentary rocks: one, without reference to composition and character, is based upon the period of their formation in the geological time scale; the other is founded on composition and physical characters. According to the first, strata are classified as Cambrian, Devonian, Jurassic, Tertiary, etc.; according to the second, as sandstones, limestones, etc. The first has its bearing in historical geology; the second is the petrological method, and is the one that concerns us here. In this work the following classification is adopted.

Classification of Sedimentary Rocks.

1. Material of Chemical Origin, from solutions.
    - *a.* Deposits from concentration.
        - Sulphates; GYPSUM and ANHYDRITE.
        - Chlorides; ROCK SALT.
        - Silica; GEYSERITE and related rocks.
        - Carbonates; TRAVERTINE and related rocks.
        - IRON ORES of several kinds.
    - *b.* Deposits formed by the agency of organic life.*
        - Carbonates; LIMESTONE and DOLOMITE.
        - Silica; FLINT and related rocks.
        - *Phosphate rock.*
        - COAL, *asphalt,* etc.
2. Material of Mechanical Origin.
    - *a.* Water-laid deposits.
        - CONGLOMERATES and BRECCIAS.
        - SANDSTONES.
        - SHALES.
    - *b.* Wind-laid deposits.
        - *Loess.*
        - *Dune sands.*
        - *Volcanic ashes.*
    - *c.* Ice-laid deposits.
        - *Tillite.*

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* Geyserite, Travertine, and Iron Ore may be also partly organic.

In the nature of things a classification of sedimentary rocks cannot always draw exact lines between different kinds of rocks. Shales may pass into limestones on the one hand, and into sandstones on the other, and no sharply defined boundary can be drawn between them. Many such instances could be cited. It would also be difficult to know just where to assign many rocks of mixed materials and origin. The classification must be considered as based upon clear and unmistakable types, which serve as center points around which the rocks group themselves. In the descriptive portion which follows, the exact order of this classification, in respect to some minor rocks, for convenience in reference, may not be always exactly followed.

CHAPTER IX

DESCRIPTION OF SEDIMENTARY ROCKS

Chemical Deposits by Concentration and Organic Agencies

The more important of the deposits produced from aqueous solutions by the material becoming insoluble through concentration are gypsum, anhydrite, rock salt, and calcium carbonate. Certain deposits of silica from hot waters should also be placed here, and iron ores as well, although in the latter the process of deposition is not usually one of simple concentration. The connection between gypsum, anhydrite, and rock salt, in respect to their origin and occurrence, is very close. They are formed in bodies of sea-water that have been separated from the ocean by the raising of coast-lines, or by accumulations of deposits, and under such climatic conditions that the isolated body of water becomes concentrated by evaporation to such a degree that its salts must crystallize out of solution and deposit. Or in a similar way they may be formed in inland lakes that have no outlet and are in arid regions, where the evaporation equals or exceeds the amount of inflow. All natural flowing waters contain more or less of various salts in solution, and in such a lake they must accumulate until the point of saturation is reached.

Gypsum

As a rock, gypsum is fine-grained to compact. Sometimes it is a foliated aggregate showing the excellent cleavage of the mineral, and sometimes it has a fine fibrous structure; but these forms are less common than the first one. The foliated type is sometimes cavernous, with crystal ends projecting into the cavities; this may result from recrystallization of the more compact varieties. The fibrous variety is more likely to occur when gypsum forms thin layers or lenses in shales and sandstones. The usual color is white, but it is sometimes yellow or red from iron oxides, or gray to dark gray from mingled clay or organic matter. It is soft and easily scratched with the finger nail. For other properties reference may be had to the description of gypsum as a mineral.

Gypsum is generally accompanied by a great variety of minerals, depending on the local occurrence. The most common and intimately related of these are rock salt and anhydrite, the three having a common origin as previously stated. Clay, marl, and bitumen are common impurities. Dolomite, calcite, quartz, sulphur, and iron pyrites are not uncommon accessory constituents. Varieties containing bituminous substances generally yield a disagreeable odor when broken. Gypsum is used in the manufacture of plaster of Paris, as a minor ingredient in Portland cement, and in the raw state as a fertilizer (land plaster). The very compact white or tinted varieties are sometimes called *alabaster*, and are cut into ornamental forms, vases, etc.

Occurrence. Gypsum is widely distributed in the sedimentary rocks, in the form of extensive beds, often of great thickness, and is especially associated with limestones and shales. It commonly accompanies beds of rock salt and as a rule underlies the salt. It also occurs in other sedimentary formations, especially in clays and shales, in lenticular masses or in isolated crystals, sometimes of great size, as in the Cretaceous beds of the western United States.

It also occurs in volcanic regions, around fumaroles, where sulphurous vapors are escaping, and especially where limestones have been subjected to such action. In some places its presence in rocks may be due to the oxidation of iron pyrites and a chemical reaction of the product with calcium carbonate.

Anhydrite

As a rock, anhydrite is a compact to fine granular substance; sometimes coarse and showing the apparently cubic cleavages of the individual grains. It may be somewhat translucent, and usually has a somewhat splintery fracture with a shimmering or pearly luster. Its color is generally white, though, like gypsum, it is often tinted reddish, yellowish, bluish, gray, or dark by oxides of iron, commingled clay, or organic matter. It is harder than gypsum but easily cut with a knife. For the other properties, see description of it as a mineral. The most commonly associated minerals are rock salt and gypsum, but locally it may contain many others, as those stated under gypsum. In the anhydrite beds in the strongly folded regions of the Alps, the clay impurity has been converted into cyanite, sillimanite, mica, etc.

The occurrence of anhydrite is similar to that of gypsum, which it frequently accompanies. It is changed on exposure to the air into that substance. The beds do not usually show any distinct stratification. In America, extensive deposits occur in Nova Scotia.

Rock Salt

This is an aggregate of grains of common salt (halite, or sodium chloride). It is sometimes fine, sometimes medium, and sometimes coarse-grained. The color is white, but it is often red or yellowish from oxides of iron, or gray from intermingled clay or organic matter, and the latter may at times produce bluish or greenish tints. The properties of halite are mentioned in the chapter on rock minerals.

Associated minerals sometimes found in the salt are quartz, anhydrite, and sometimes, though rarely, carbonates or pyrite.

Rock salt occurs in geological formations of the sedimentary rocks of all ages and in many parts of the world. The beds vary greatly in thickness, from one foot to 400 feet or more. Such enormous thicknesses cannot be explained by the simple evaporation of an isolated body of sea-water along an arid coast line. There must have been subsidence gradually going on; at first the less soluble gypsum, and then the salt, would be deposited, leaving a mother liquor containing the more soluble sulphates and chlorides of magnesium and potassium. If subsidence and the lowering of the barrier should now occur, there would be an influx of the lighter sea-water above, while the heavier mother liquor would flow out below and the basin would be charged anew with sea-water. If the barrier were again closed, for example by waves building it up as seen along the coast of the Carolinas, the conditions would be repeated and fresh deposits of gypsum and salt formed. Thus by repetitions of such a process we can imagine that great thicknesses of salt might be locally deposited. Finally, if no outflows occur the mother liquor is also evaporated and the more soluble salts deposited.

In the United States rock salt occurs in beds in New York, Michigan, Louisiana, Texas, Kansas, and various other states. It is found in Germany, Austria, and Poland in vast deposits; in several counties of England and in many other places. Interior drainages are present in all of the continents and in connection with them there are salt lakes and deposits of salt.

Flint, Geyserite, and Other Siliceous Rocks

Deposition of silica, SiO_2, from its solution in water occurs both by simple concentration and evaporation and by the action of organic life. It is possible that it also happens as a result of chemical reactions. The deposits thus formed, while lacking the wide extent and geologic importance of the sedimentary formations produced by the processes of erosion, nevertheless have considerable interest and may be of local significance. On account of their general similarity of composition they are here included under one heading, but the group does not include the mechanically formed siliceous sandstones. The material composing these rocks is, mineralogically, sometimes in the form of quartz — pure crystallized SiO_2, and sometimes in the form of opal or chalcedonic silica — uncrystallized silica containing more or less water in combination.

Flint. This is a dark gray or black rock, so extremely compact that it appears as a homogeneous substance. The fracture is conchoidal and the chips have a translucent edge like many felsites, which indeed this rock may closely resemble. The hardness is 7. Flint consists of an intimate mixture of quartz and opal, the coloring matter being organic and disappearing when a chip is heated before the blowpipe.

Flint is not a rock in the sense that it occurs in extended independent formations. It occurs in irregular nodules or concretions in chalk which vary widely in size, from that of a pea to extensive layers. Similarly an impure flint, occurring chiefly in limestones from the Cambrian up, is called *chert.* When these substances are studied under the microscope they are found to contain the hard siliceous parts of various organisms, chiefly of sponges and radiolarians. The matter was first derived from sea-water by such organisms, but appears secondarily to have gone into solution and been chemically deposited around certain centers, and in certain places, where favorable conditions obtained. The uses of flint for savage and prehistoric implements and weapons and for striking fire are well known. Other siliceous masses, similar in a general way to flint and chert, sometimes of the same and sometimes of uncertain origin, have received various names such as *lydianite*, *hornstone*, etc. *Jasper* is a chemically precipitated opaline silica. In places, as in the Lake Superior region, the jaspers are strongly ferruginous and interlaminated with bands and streaks of hematite. They constitute rock masses of considerable size, the so-called iron formations, affording valuable deposits of iron ore. They are called *taconite.* The cherty layers are colored bright red by the iron oxide. Another variety of these siliceous flint-like rocks is *novaculite*, which occurs in considerable beds in Arkansas, and is extensively used in the manufacture of whetstones and hones. It is extremely fine-grained, conchoidal in fracture, white or pale gray, semi-translucent, and composed of silica. It is regarded as a chert that has been metamorphosed by the intense folding to which it has been subjected.

Geyserite. Siliceous Sinter. In volcanic regions silica is frequently deposited by hot waters, boiling springs, and geysers. Sometimes this is produced by simple evaporation and drying of the water, and sometimes, as shown by Weed, it is due to vegetable organisms, *algæ*, which become coated with silica that they have secreted from the heated waters in which they live. The material of the geyser cones and basins produced by drying is hard, compact, and opaline, while that formed by the plants is more or less loose and spongy. If pure, it is white in color. Its formation is well illustrated in the hot spring and geyser areas of the Yellowstone Park and New Zealand (see Plate 27). The material thus formed is known as geyserite, or siliceous sinter.

Diatomaceous Earth. This is a soft, white, chalk-like, very light rock composed of innumerable microscopic shells of diatoms. The latter are excessively minute, one-celled organisms which possess free motion and are covered with a siliceous shell of great delicacy; they are considered forms of vegetable life. They live in both fresh and marine water. In waters of suitable character they may swarm in incredible numbers, and their shells, accumulating at the bottom, may give rise to deposits of considerable magnitude. Some varieties of the rock are pale yellow, brown, or gray. It is easily distinguished from chalk, which it may resemble, by its non-effervescence with acid; from clay, by its gritty feeling, when rubbed between the fingers, and its weak argillaceous odor or absence of odor. A more positive test is the effervescence produced when it is mixed with sodium carbonate and fused before the blowpipe. The loose, scarcely coherent material is called *infusorial earth;* when more compact it is sometimes called *diatomite.* It is extensively used for polishing purposes and for a wide variety of other uses, such as insulating material, etc. Beds of considerable magnitude occur in Maryland, Virginia, Georgia, and Alabama, where they are worked commercially, also in Missouri, Nevada, California, and elsewhere, often as a layer in swamps that represent the fillings of former lakes. Marine diatomites of Miocene age attain a maximum thickness of 5000 feet in the Coast Ranges of California; they are regarded as the source rocks from which the enormous amounts of oil of that region were derived. Diatomaceous deposits are also found in Germany and other parts of Europe.

PLATE 27

GEYSERITE, SPIKE SPRING, YELLOWSTONE PARK.

(U. S. Geological Survey.)

Iron Ore Rocks

The deposits of iron ore which occur as rocks, interstratified or associated with sedimentary beds, have originated through complex processes, sometimes wholly, sometimes partly, of a purely chemical nature, and usually more or less influenced by the agencies of organic life. The most important set of processes has been previously mentioned but now deserves a more detailed description.

Iron exists in the original (the igneous) rocks as disseminated grains of silicates, such as biotite, olivine, pyroxene, and hornblende, and also of oxides, such as magnetite, hematite, and ilmenite. It also occurs in the secondary metamorphic rocks as silicates and oxides. It is quite generally diffused through the sedimentary rocks, in part as coloring matter and cement, and mostly in the form of ferric oxide, ferric hydroxides, and ferrous carbonate. In the igneous rocks it is largely in the ferrous state, and to a considerable degree also in the metamorphic ones. Moreover, to understand the concentration of iron and formation of iron ore rocks, it must be borne in mind that the metal forms only one carbonate, ferrous carbonate or siderite, $FeCO_3$, which, like calcium carbonate, is soluble in water containing carbon dioxide.

When the rocks are decomposed and broken down by the agencies of weathering and erosion, the silicates containing iron are altered; the ferrous iron in them combines in part with the carbon dioxide in the circulating ground water to form ferrous carbonate which goes into solution, and in part it is oxidized to ferric hydrate. The original oxides of iron react in a similar manner. The ferric hydrate thus formed or liberated would be insoluble, but in the presence of decaying vegetable matter in the soil and organic acids leached downward into the rocks, deoxidation of the ferric iron ensues; it is reduced to ferrous iron and then becomes ferrous carbonate and goes into solution. The reason for this is that decay of organic matter is a process of oxidation, like slow combustion; the organic matter takes oxygen from the air, but in the presence of moisture and ferric iron it will take oxygen from the latter, reducing it to the ferrous state which is then fitted to unite with carbon dioxide and become ferrous carbonate.

The iron, which is thus brought into solution, is leached out of the rocks, and may be concentrated in standing bodies of shallow water, such as swamps, lagoons or estuaries, with small outlets to the sea, where it gives rise to extensive deposits. Under some conditions these deposits may be of the carbonate directly, but usually the solution of the carbonate is reoxidized, carbon dioxide escapes, and the iron is precipitated as ferric hydroxide (limonite). This oxidation is largely, if not wholly, performed by certain bacterial organisms which demand iron in their internal economy, and therefore secrete the iron from the water, and change it in their cells from the ferrous to the ferric condition, thus rendering it insoluble. Living and dying in unimaginable numbers, though excessively minute, they give rise to large deposits.

The ferric hydroxide which is thus precipitated may accumulate on the bottom as bog iron ore, or limonite, or, as is so often the case in shallow bodies of standing water, like swamps, etc., it may again come in contact with decaying vegetable matter, and be changed back into carbonate. Such beds of iron ore may be quite pure, or they may be more or less mingled with clay and sand, brought in at times of high water, and thus impure limonites, clay iron-stones, black-band ore, etc., are formed. This also explains the not infrequent association of stratified iron ore and coal beds in the same series of rocks, and the reason why the iron ore is then commonly ferrous carbonate.

The moving ground waters containing iron in solution, as described above, may also issue as springs and give rise to deposits of iron ore.

Certain masses of iron ore, chiefly limonite, are supposed to be residual products of weathering and solution. This is illustrated in the view that masses of limestone containing minor ferrous carbonate have been dissolved and carried away, but the iron, oxidized to the ferric condition in the process, has become insoluble and, remaining behind, has gradually concentrated. The more important iron ore rocks may now be described.

Bog Iron Ore. Limonite. Bog iron ore is sometimes loose and earthy, sometimes firm and porous. It consists mainly of limonite, mixed more or less with humus, phosphates, silicates of iron, clay, sand, etc. Its character has been sufficiently described under limonite among the minerals. It sometimes occurs in concretions. With increasing amounts of clay it passes over into *yellow ocher*. It is found in all parts of the world. In the United States it is widely distributed. Along the Appalachian belt, from Vermont to Alabama, deposits of limonite, most of which are probably residual in character, have furnished iron ore since the early settlement of the country, and in great quantity.

Clay Ironstone. Siderite. When reasonably pure, siderite, or spathic iron ore, is a coarse to fine crystalline aggregate of siderite grains. It is whitish to yellow, or pale brown in color, but on exposed surfaces is much darker brown to black, owing to oxidation of the ferrous carbonate to limonite, or of the manganous carbonate to manganic oxides. It generally contains, in varying amounts, carbonates of calcium, magnesium, and manganese. Iron pyrites or hematite are commonly associated minerals. The properties of siderite are given in its description among the minerals.

An impure variety of siderite, mixed with clay, sand, and limonite in variable proportions, of a compact appearance, and generally of dull brown colors, is known as clay ironstone. It is likely to occur in nodules, often as concretions around some fossil, and as lenticular masses which increase until they become interstratified beds of considerable thickness. Another variety, which contains so much organic, coaly matter that it is colored black, is known as *black-band* ore. It is especially associated in the strata with coal beds from the Carboniferous upward.

Carbonate ores of iron are of less importance in the United States than the deposits of limonite and hematite. They occur in Pennsylvania, Ohio, and Kentucky, of Carboniferous age, and in the Lake Superior region in Michigan and Minnesota, of Algonkian age. They occur in Europe, in England, Germany, France, and Spain, in deposits of great technical value. Black-band is found in the coal-bearing strata of Pennsylvania, England, etc.

Hematite. Red Iron Ore. This occurs in the form of veins, lenticular masses, and beds, in various geological formations and especially in those in which the strata have been folded. As a rock, it varies from fine-grained and compact to earthy or fibrous, is of a red to brown color or, where crystalline, of a dark gray. Its properties as a mineral have been previously given. It occurs pure or nearly so, but with varying mixtures of clay, sand, or silica it passes insensibly into ferruginous clays, red ochers, or shales, sandstones, cherts, etc. In this connection see taconite under flint. While hematite undoubtedly occurs as a normal sedimentary or stratified rock interbedded with other unchanged strata, as in the beds which have such a wide distribution in the eastern United States in the Clinton group of the Niagara period, it is more generally to be considered a metamorphic rock, and as such, might be included among the metamorphic iron rocks described in Chapter XI, such as itabirite and hematite schists.

Extensive deposits of hematite are found in various parts of the United States and Canada. The greatest amounts mined as ore come from Alabama and the Lake Superior region, the vast production in the latter leading the world in output. Large beds are also found in England and other parts of Europe.

Iron Oölite. The iron rocks described above, and especially red hematite, not infrequently assume a concretionary form in which the rock is composed of rounded, sometimes polygonal, grains which vary in size from that of fine sand to peas. An examination of them shows that they have a concentric shelly structure. The color varies from red to brown. Sometimes the rock is composed of them alone and sometimes they are thickly embedded in a marly or clayey cement. The iron ore appears in many places to have been deposited around grains of sand, fragments of fossils, etc., as nuclei. The Clinton ores mentioned above frequently assume this oölitic character and it is well known from various European localities. Such ores have sometimes been changed into magnetite while still retaining the oölitic structure.

Limestone and Other Carbonate Rocks

This group of rocks has the common property of being composed of carbonate of calcium, calcite, $CaCO_3$, or of this substance intermingled more or less with dolomite, $CaMg(CO_3)_2$. It is also a common property that the calcium carbonate has primarily been separated from water, rendered insoluble, and accumulated by the action of living organisms of one kind or another. Secondarily, the deposits thus made may be mechanically broken up and redeposited, or they may be taken into solution, carried away, and precipitated elsewhere. There may be many exceptions to this rule that the calcium carbonate is primarily precipitated by organisms, and much of it may have been precipitated by purely inorganic agencies, such as supersaturation of oceanic waters with $CaCO_3$.

This group of rocks is soluble in hydrochloric acid; entirely so when they are pure carbonates, but generally leaving more or less of a residue, consisting chiefly of sand, clay, silica, etc. If dolomite is present, unless the rock is finely pulverized the acid must be heated. The hardness of these rocks is less than 4, hence they may be readily scratched or cut with the knife.

The following are the important members of the group.

Limestone. This is the most common and important carbonate rock. It is fine-grained to aphanitic in texture and its color varies from whitish, through tones of yellowish to brown, or from various shades of gray, dove-color, bluish-gray, dark-gray to black. It is rarely of reddish colors. The yellow and brown colors are due to iron oxide, the gray and black to organic matter. The gray colors are most common. Compact varieties have an even to somewhat conchoidal fracture.

Limestone effervesces freely with any common acid, with vinegar (acetic acid) or lemon juice (citric acid). It is easily scratched with the knife and many of the less compact varieties are friable to the finger nail. The specific gravity varies from 2.6 to 2.8. On exposed surfaces it tends to be cavernous and often tinted or blotched reddish or yellowish from oxidation of small amounts of ferrous carbonate which it may contain. It occurs in individual beds of all thicknesses up to 100 feet or more.

Some limestones consist of pure grains of calcite, others possess a fine, clay-like cement between them. Accessory minerals, which are sometimes seen, are pyrite and quartz, the latter in minute crystals, sometimes lining cavities.

In the following analyses, I, II, and III are of very pure limestones; IV is an impure type containing considerable dolomite and sand and clay. Such transitions through impurities are common; thus V for example shows one toward the clay-ironstone previously described. Transitions to dolomite are not common; an examination of a large number of analyses shows that generally either the rock contains very little or no magnesium, or it has much and is a regular dolomite as described later.

	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	H_2O	XyO	CO_2	Total
I.....	0.4	...	0.4	...	trace	54.8	1.1	...	42.7	99.4
II....	0.6	...	0.4	...	0.4	54.2	...	...	44.0	99.6
III...	1.2	0.2	0.2	0.3	0.6	53.8	0.9	0.1	42.7	100.0
IV...	7.0	3.6		...	9.0	39.3	0.2	1.2	38.8	99.1
V....	3.2	0.1	1.0	15.2	11.0	26.6	0.5	1.5	41.1	100.2

I, Trenton Limestone, Lexington, Virginia; II, Buff Limestone, Hoosier Quarry, Bedford, Indiana; III, Lithographic Limestone, Solenhofen, Bavaria; IV, Impure dolomitic Limestone, Greason, Pennsylvania; V, Sideritic-dolomitic Limestone, Gogebic Dist., Michigan.

XyO represents small quantities of organic matter, manganese oxide, etc.

The strength of limestone as a rock varies very much with the texture; that of firm, compact varieties is very high, while loose, porous ones are very weak. Thus a fine-grained variety has been shown to have a crushing strength of over 40,000 pounds per square inch, while others scarcely exceed 3000 pounds per square inch. The well-known white oölitic limestone of Bedford, Indiana, has an average crushing strength of 4300 pounds. Any good firm and compact limestone has a strength far in excess of any load that it may be called upon to endure in modern structures. The porosity of limestones varies considerably; those containing the most sand are usually the most porous. The ratio of pore space to rock volume may vary from 15 per cent to practically nothing; the ratio of the weight of water the rock can absorb to its own weight is in general much less than this, usually not more than one-half as much.

There are many varieties of limestone, depending on circumstances, especially the mode of formation. Thus in some there are abundant remains of fossils which may give the rock a distinctive character. These comprise a great variety of organisms, among which may be mentioned corals, crinoids, shells of mollusks, brachiopods, bryozoans, foraminifera, remains of sponges, etc. The "encrinal limestone" of Silurian age in western New York is an example. Sometimes these fossils occur in such numbers that the entire rock is composed of masses of shells, or of the hard parts of one particular organism, with just enough fine calcium carbonate between them to act as a cement. Examples of this are seen in the layers composed wholly of brachiopod shells found in the Niagara formation of the Silurian in western New York. Such rocks are sometimes called "shell limestones." Certain limestones composed of corals are also examples of the same thing.

On the other hand, there are varieties which depend on the presence of some impurity which gives a particular character to the rock. Thus it may contain much clay and be termed an *argillaceous limestone* or it may contain much sand of siliceous character and be an *arenaceous limestone:* such rocks are transitional to shales and sandstones. Others, which are dark-colored, may yield a strong, disagreeable, bituminous odor when struck and broken and are called *bituminous limestones;* they contain considerable organic matter. In some, which are termed *glauconitic limestone,* the rock is more or less filled with green grains of glauconite.

Lithographic stone is an extremely fine-grained (homogeneous) limestone; the flesh-colored rock from Solenhofen, Bavaria, remarkable for the well-preserved fossils it occasionally contains, is especially used for this purpose. It is a very pure limestone, as shown by the analysis given above.

Limestones frequently contain concretions and masses of chert, or hornstone, of the character described in a previous section, which often become so abundant as to form definite bands or layers in the rock.

By the weathering of limestones the calcium carbonate is removed in solution, leaving the insoluble impurities behind. The impurities thus concentrated form clays or loams which are colored deeply red or yellow by the oxidation of the iron minerals originally present, and commonly contain pebbles of chert or quartzose material and masses of limonite. Such residual soils are commonly very fertile and cover large areas in the southern United States, and in other parts of the world.

Uses of Limestone. The use of limestone for structural purposes of all kinds is well known and needs no further comment. The same is true of its manufacture, by burning, into quicklime for mortar and cements. Large quantities are also used as a flux in smelting operations, as in the making of iron and steel. In recent years the use of certain impure limestones containing 15 to 40 per cent of clay, or other substances consisting of silica, alumina, and iron oxide, in the manufacture of natural hydraulic cements has risen to very large proportions.

Dolomite. The geological use of this term is not always the same as the mineralogical one. Mineralogically, by dolomite is meant a chemical compound of a definite composition, $CaMg(CO_3)_2$, with CaO 30.4 per cent, MgO 21.7, CO_2 47.8; geologically, the term is used for any limestone that consists dominantly of this compound, although it may also contain a large amount of admixed calcite, $CaCO_3$; and in parts of Europe it is employed to designate limestones of a particular geological period, some of which are not dolomites at all.

The description of the colors, texture, and other physical characters of limestone, given above, applies equally well to dolomite. In fact, it is not ordinarily possible to determine in the field, or by mere inspection of a hand specimen whether a rock is a dolomite or a pure limestone.

Dolomite is somewhat harder than true limestone, and if the specimen is a pure dolomite it will not dissolve with effervescence in acetic acid (vinegar) and but very slowly in cold hydrochloric; but if the dolomite is finely pulverized it will effervesce freely even in cold acid. The best test is a chemical one for magnesium in a solution obtained by boiling the powdered rock in dilute hydrochloric acid.

The following analyses show the chemical composition of some examples of this rock.

	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	CO_2	H_2O	XyO	Total
I.....	3.2	0.2	0.2	0.1	20.8	29.6	45.5	0.3	...	99.9
II....	3.1	...	0.1	0.9	20.0	29.7	45.3	0.3	0.2	99.6
III...	1.1	0.4	...	...	19.9	31.5	45.6	1.3	0.1	99.9
IV ...	5.0	1.0	0.5	...	16.8	32.2	43.8	...	...	99.3

I, Knox Dolomite, Morrisville, Alabama; II, Dolomite, Sunday Lake, Gogebic district, Michigan; III, Dolomite, Tornado Mine, Black Hills, South Dakota; IV, Dolomite (magnesian limestone), Newcastle, England.

The origin of dolomite is a matter which has been much discussed, and many theories have been propounded by geologists and chemists in explanation of it. When all the facts are taken into consideration, it is clear that dolomite is not an original rock, but has been formed from pure limestones by the replacement of a part of the calcium by magnesium, from waters containing magnesium salts in solution. Dolomite is a denser and more stable compound than calcite; if the latter were subjected to the action of soluble magnesium salts there would be a constant tendency for dolomite to form and for part of the calcium to be removed, as illustrated in the following reaction,

$$2\,CaCO_3 + MgCl_2 = CaMg\,(CO_3)_2 + CaCl_2.$$

It is evident that if the magnesium solution were strongly concentrated, the exchange, in a given mass of limestone, would be effected more quickly. If the solution were heated it would also act more quickly; if it acted under pressure the result would also be hastened, and, finally, as time is an important element, the longer the limestones have been subjected to the solutions the more completely we may expect them to be changed to dolomite. If we consider, in addition, that not only sea-water, but also the circulating ground waters and thermal waters ascending from the depths, contain magnesium salts in greater or lesser amount, it is clear that in harmony with the above principles, the change, which we may call *dolomitization*, must take place in a variety of ways and under various conditions, not only in the sea, but also on the land. That all limestones are not converted completely into dolomite before they emerge from the sea must be due to certain reasons: the solution is too dilute, it is not hot enough, there has not been sufficient time, the deposits are too compact to permit sufficient penetration and circulation of sea-water, etc. But if calcareous deposits are subjected in an enclosed basin to constantly concentrating sea-water they may become more rapidly converted. This might happen, for instance, if a coral atoll were somewhat elevated and its lagoon wholly or nearly shut off from access to the sea. The application of the principles stated above would also lead us to conclude that the older and more deeply buried a limestone was, the more likely it would be to become a dolomite; that in disturbed and folded mountain regions, limestones of the same age and formation would be more likely to be dolomitic than those of undisturbed areas, because the rocks are there more fractured and filled with thermal solutions. In practice the facts are found to confirm these views. The connection with thermal waters also explains the frequent association with lead and zinc ores.

The mineral dolomite is denser than calcite and in the change above mentioned a considerable reduction of volume, amounting to 12 per cent, must occur in the limestone. This reduction of volume would apparently help to explain why some dolomites are porous or cavernous rocks, though if deeply buried, all such cavities would be closed by the pressure.

Limestones and dolomites are rocks of such general distribution in all parts of the world where stratified rocks are found, that their occurrence needs no special mention.

Oölite. Oölitic Limestone. This is a well-characterized variety of limestone, consisting of minute to small spherical concretions, presenting very much the aspect of a fish roe, whence the name from the Greek, meaning egg-stone. The round grains vary in size, some being very minute and some as large as a pea. In the larger ones it may often be observed that they have a concentric shelly structure and thus consist of successive coats. An illustration of a coarse oölite or pisolitic limestone from Bohemia is shown in Plate 28. There is usually more or less limy cement binding the grains together.

Examination of oölites generally shows that some object, such as a bit of shell, a grain of sand or something similar, has served as a nucleus around which the coatings of lime carbonate have accumulated. On the shores of Great Salt Lake at the present time oölitic sands are forming from the waters which are charged with lime and other salts in solution. As the particles are rolled on the beach, or agitated in the water, all parts become equally coated and the spherical form is assumed. By a similar process oölitic grains are forming in springs charged with calcium salts, as at Carlsbad in Bohemia. The concretionary structure is best seen under the microscope; it is rarely sufficiently coarse to be observed with the eye alone, but may be sometimes made out with a lens. Oölitic limestones constitute large and important formations, often of great thickness and of different geological ages. They are especially important in the Jurassic strata of England and elsewhere in Europe. Oölitic structure is also assumed by some American limestones.

Chalk. Typical chalk is a soft, white, friable rock, well known from its use for marking and blackboard crayons. While generally pure white it may sometimes be tinted gray, flesh color, or buff. It consists of a fine calcareous powder, which by examination under the microscope has been found to consist of the tiny shells of foraminifera, mingled with minute fragments of the shells and hard parts of various organisms, as well as the siliceous spicules of sponges, shells of diatoms and radiolarians, together with occasional microscopic fragments of various minerals. It is the siliceous material of the sponge spicules, diatom shells, etc., that has concentrated into the nodules and concretions of flint, so commonly found in certain beds of chalk, and the analogue of which is seen in the layers and masses of chert in limestones. Chalks, in spite of their fine grain, are very porous rocks, absorbing as much water as 20 per cent of their weight in some instances.

Chemically, chalks are quite pure calcium carbonate, as shown in the following analyses of three specimens given by different authorities.

It was formerly customary to consider chalk a formation produced on the bottom of the deep sea, from its resemblance to the calcareous oozes or muds found underlying the depths of modern oceans. It has evidently not been formed in this way, as shown by the fossils indicative of shallow water which some chalks contain, as well as the perfect skeletons of birds, pterosaurs, and other vertebrate animals. The facts point rather to its having been formed in clear, warm, and shallow seas, free from the products of land waste.

Closely related to chalk, but differing in the fact that they do not predominantly consist of foraminiferal shells, are light, chalky, earthy limestones formed in a variety of ways, such as from coral sands and muds, from those materials accumulated by the wind on coral islands, from ground-up shells in clear, shallow seas, etc. A whitish, fragile rock formed on the coasts of Florida, consisting of shells and their fragments of all sizes somewhat lightly compressed and cemented together, is known as *coquina*, from the Spanish word for shell. (See Plate 28.)

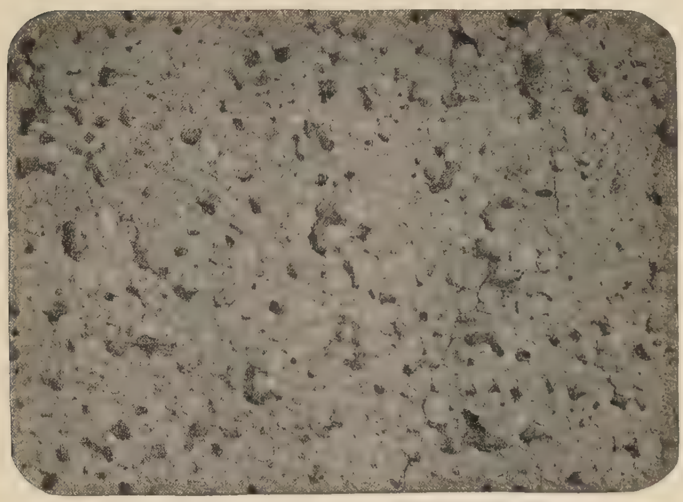
	$CaCO_3$	$MgCO_3$	SiO_2	$(Fe,Al)_2O_3$	H_2O	Total
I........	94.2	1.4	3.5	1.4	0.5	101.0
II.......	96.4	1.4	1.6	0.4	0.2	100.0
III......	98.4	0.1	1.1	0.4	...	100.0

I, White chalk, White Cliffs, Little River, Arkansas; II, Lower Cretaceous chalk, Burnet Co., Texas; III., White chalk, Shoreham, Sussex Co., England.

Chalk is found extensively in Europe, in England, Germany, France, etc., where its occurrence is the result of a distinct geologic epoch, named on this account the Cretaceous. It also occurs widely distributed in the Cretaceous formations of Nebraska, Alabama, Arkansas, and especially in Texas.

Travertine, Calcareous Tufa. In the preceding chapter it was shown how material of the land surface is taken into solution and carried into the sea. This is especially important with regard to calcium, which goes to the sea as a sulphate and carbonate, the latter being much the more abundant. This calcium carbonate comes not only from pre-existent carbonate rocks but also from the calcium silicate minerals of the igneous and metamorphic ones, which under atmospheric agencies are

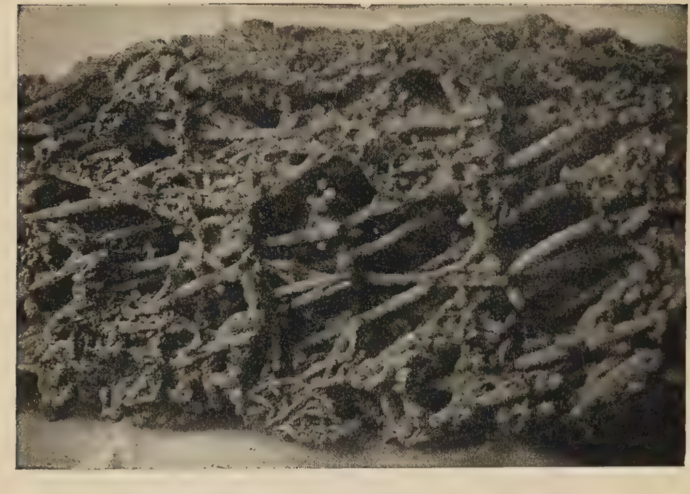
PLATE 28.



A. OÖLITE, VARIETY PISOLITE, BOHEMIA.

B. COQUINA, FLORIDA.

PLATE 29.



A. CALCAREOUS TUFA, DEPOSITED ON VEGETATION, COLORADO.

B. CALCAREOUS TUFA, YELLOWSTONE PARK.

(U. S. Geological Survey.)

converted into carbonates. The calcium carbonate on its way to the sea may be temporarily deposited, giving rise to rock masses of some magnitude and importance.

Carbonate of calcium has little solubility in pure water, but if the water contains carbon dioxide the calcium carbonate is converted into a soluble bicarbonate, and the amount of the latter formed and taken into solution depends on the amount of carbon dioxide present. Thus in regions where limestones or other carbonate rocks abound, the natural waters, under atmospheric pressures, attack such rocks and take the calcium carbonate into solution in a relatively slow manner, but in spring waters, and especially thermal ones coming from depths, the pressure may be great, the amount of contained carbon dioxide large, and the quantity of dissolved calcium carbonate proportionately so. Such waters on coming to the surface lose the greater part of the dissolved carbonic acid in the form of gas, and the calcium carbonate in solution is consequently deposited rapidly and in large amount. In the waters under surface atmospheric pressure the calcium carbonate is deposited by evaporation and therefore much more slowly. In warm waters the deposit of calcium carbonate may be much increased by the action of low forms of vegetable life, algæ, living in them, which secrete calcium carbonate from the water.

The rock thus formed by deposit of calcium carbonate from solution is called *travertine*, from the old Roman name of the town of Tivoli near Rome, where an extensive formation of it exists. When deposited slowly, as in the stalactites and stalagmites in caves, it is rather hard and compact, fine crystalline, sometimes white but usually tinted yellowish or brownish; it often has a fibrous or concentric structure; it breaks with a splintery fracture. When deposited more rapidly, as by springs, it is softer, not evidently crystalline, and porous to loose or earthy; when formed as a coating on vegetation it may be open, cellular, spongy, bladed, or moss-like, as illustrated in Plate 29.

These looser, less compact, varieties are commonly called *calcareous tufa* or *calcareous sinter*. Deposits of travertine, or calcareous tufa, are found in nearly all countries and especially in limestone regions. Many caves are celebrated for the number, size, and beauty of the stalactitic and stalagmitic formations they contain. See Plate 30. Springs depositing calcium carbonate are very common, but warm carbonated waters are chiefly found in volcanic regions or those which have recently been volcanic, like the celebrated Mammoth Hot Springs of the Yellowstone Park, and others found in California, Mexico, Italy, New Zealand, etc. See Plate 31. The so-called Mexican "onyx" or "onyx marble," which is extensively used as an ornamental stone, is a travertine with a banded structure, beautifully brought out by its varied tinting through metallic oxides.

Marl. This name is given to loose, earthy or friable deposits consisting chiefly of intermingled calcium carbonate or dolomite with clay, in variable proportions. The color is usually gray, but they are often yellow, green, blue, or black, and sometimes with pronounced color tones due to some special substance, as oxide of iron or organic matter. They show all gradations into clays and shales. On exposure to the air or water they crumble quickly into coarse soils. The carbonates in them are readily detected by their effervescence in acid. Different varieties are named, according to special substances or objects which they may contain in addition to those mentioned; thus *sandy marl* is full of grains of quartz sand and often of other minerals; *shell marl* is a whitish, earthy deposit made up of fragments of shells of various organisms formed in enclosed basins of water, mingled with clay, etc. In the Atlantic and Southern states this name is applied to beds that contain in abundance the shells of corals, gastropods, and other shell-fish.

The chemical composition of marls varies very greatly; the following analysis of a compact one from Colorado will serve as an example.

$CaCO_3$	$MgCO_3$	SiO_2	Al_2O_3	Fe_2O_3	MgO	K_2O	H_2O	Org. Sub.	XyO	Total
21.6	1.7	45.9	13.2	3.9	1.3	2.3	5.4	3.5	1.2	100.0

XyO = small quantities of TiO_2, Na_2O, and P_2O_5.

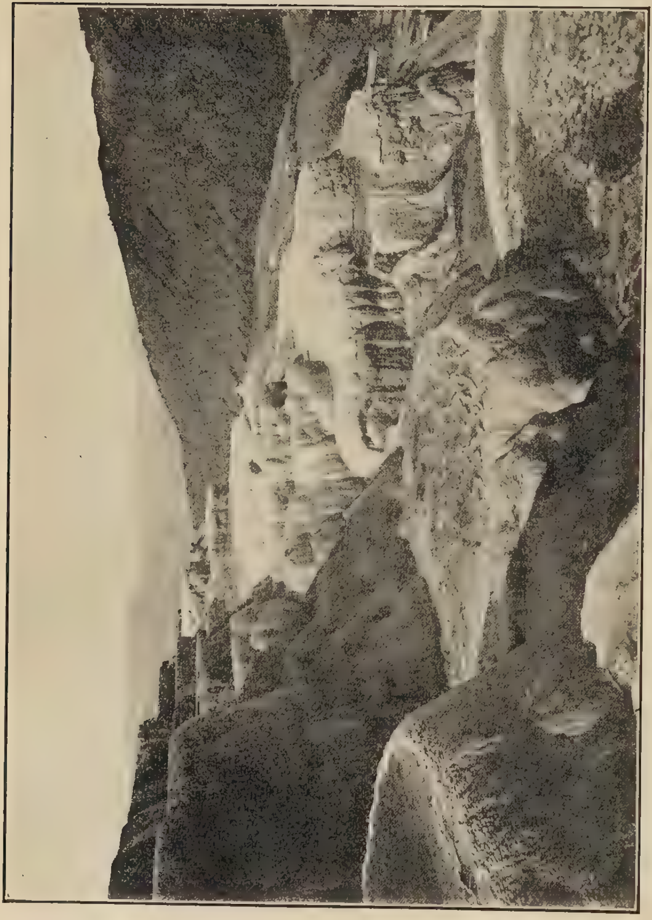
Greensand Marl is described under sandstones.

PLATE 30.

STALACTITES OF TRAVERTINE IN LURAY CAVERN, VIRGINIA.

(U. S. Geological Survey.)

PLATE 31.



TRAVERTINE BASINS, MAMMOTH HOT-SPRINGS, YELLOWSTONE PARK.

Phosphorite — Phosphate Rocks

Deposits of calcium phosphate, while not of great geological importance in making extensive formations, are yet of considerable interest and, commercially, of great value, from their use as soil fertilizers. When occurring in stratified rocks and unconnected with igneous intrusion they represent material of organic origin. While some invertebrates, such as a few species of brachïopods, secrete calcium phosphate in their shells and hard parts, it is mostly to the bones and excrement of vertebrates that the origin of this material must be ascribed. Some deposits appear to be the direct and original ones, but others are secondary in nature, in that the phosphates have been leached out, carried down, and redeposited as nodular, concretionary, or lenticular masses in clefts and other cavities in the rocks in which they occur. Especially in limestones, which, being soluble, are carried away, the less soluble phosphatic material tends to accumulate in such masses. The general name of phosphate rock, or *phosphorite*, may be used for all such material. The appearance of these rocks is variable, sometimes compact, semi-crystalline, fibrous, or concretionary; often cavernous or spongy; sometimes in rounded mammillary forms; in other cases more or less earthy. The color is usually gray, but sometimes white, buff, reddish, bluish, or even black. The simplest test for these phosphates is to dissolve a powdered sample in nitric acid, and, after filtering off the insoluble matter, to add an excess of ammonium molybdate solution and ascertain by the yellow precipitate if phosphorus is present. The general chemical composition is shown in the following analyses of samples from various localities in North Carolina.

Sand and insoluble matter	1.5	31.2	22.1	23.4
Calcium carbonate	12.0	15.9	42.1	64.3
Calcium phosphate	71.8	42.1	20.5	11.2
Water and other constituents	14.7	10.8	15.3	1.1
Total	100.0	100.0	100.0	100.0

Phosphorites are widely distributed; in the United States they are found extensively in Florida, in Tennessee, and especially in Idaho. They occur in Russia, Tunis, Algeria, Morocco, and various islands of Oceania.

Coal and Other Carbonaceous Rocks

It is well known that, interbedded with other stratified rocks of the different geological periods down to the present, there occur layers of carbonaceous character, which, under the names of coal, lignite, etc., represent the remains of former vegetable life, which once flourished where these beds are now found. The formation of peat in modern lakes, swamps, and bogs, and its occurrence in beds interstratified in recent delta deposits with those of sands and clays, as in the Mississippi delta, shows us how these beds of coal were formed. It is possible to trace every step of the gradual transition, from the growing vegetation of today into peat, from this into lignite or brown coal, and so on into bituminous coal, then into anthracite, and eventually into graphite or practically pure carbon.

The vegetable matter composing plants consists for the most part of carbon, hydrogen, and oxygen. Its decay in the air, like combustion, is a process of oxidation; the hydrogen goes off as water, the carbon as carbon dioxide, the oxygen of the air assisting that in the vegetable matter to effect the change. In this process most of the carbon is removed. If the decay takes place under water, however, the access of the oxygen of the air is prevented and the process becomes much like that where wood is burned with a limited amount of air to form charcoal. Some of the carbon unites with some of the oxygen to form carbon dioxide; some of the hydrogen unites with the rest of the oxygen to form water; the rest of the hydrogen unites with some of the carbon to form marsh gas (methane); and the remainder of the carbon is left behind. This can be illustrated by the following equation in which the formula of cellulose, which comprises the most important part of vegetable matter, is used.

$$\begin{array}{ccccccccc} \text{Cellulose} & & \text{Carb. Diox.} & & \text{Water} & & \text{Methane} & & \text{Carbon} \\ C_6H_{10}O_5 & = & CO_2 & + & 3\,H_2O & + & CH_4 & + & 4\,C. \end{array}$$

It is not intended to imply that this change takes place at once, or is complete, under water; it goes on gradually, and as the CO_2 and CH_4 are evolved, the residual matter becomes richer in carbon and poorer in hydrogen and oxygen. Thus vegetable matter is converted into peat, and this by compression and further change into brown coal or lignite. The same process goes on in coal beds, furnishing the deadly gases known to the miners as choke-damp (CO_2) and fire-damp (CH_4), and lignite thus changes to bituminous coal. Folding of the strata, with compression and heat, and the consequent rupturing and fissuring of the overlying beds, which permits the easy escape of the gases, hasten the process, and under such circumstances the coal is changed to anthracite, which is much richer in carbon, or even into graphitic coal, which is practically pure carbon. Thus the degree to which lignite has advanced through bituminous coal to anthracite depends in part on its geological age, and in part on the conditions to which it has been subjected.

Peat. This varies from a brown to yellowish matted mass of interlaced fibrous material, strongly resembling compressed tobacco, in which remains of plant leaves, stems, roots, etc., are still recognizable, in the upper portion of the bed, to a dark brown, or black, compact, homogeneous mass appearing much like dark clay when wet, in the deeper, lower parts. A dried, compact, very pure peat from Germany is stated to have the following composition:

Carbon	Hydrogen	Oxygen	Nitrogen	Ash	Total
55.9	5.8	36.4	1.0	0.9	100.0

It has been found that under enormous pressure peat may be artificially converted into a hard, black substance like coal. The wide distribution of peat and its use as a fuel are too well known to need further mention. Its purity depends on the amount of clay and sand mingled with it in the process of formation; even the purest peat, like coal, has a small percentage of ash resulting from the mineral constituents in the plants.

Lignite. Brown Coal. This is usually a chocolate brown in color, but varies to yellowish or black; compact and firm to earthy and fragile; luster dull and soft to pitchy; often shows distinctly the texture and grain of wood or intermatting of vegetable fibers. Hardness varies from 1 to 2.5, the specific gravity from 0.7 to 1.5. It burns readily with a smoky yellow flame and strong odor. The carbon in it varies from 55 to 75 per cent. A high water content is characteristic of lignite; in some it is as high as 40 per cent. A lignite from Germany is stated to have the following composition which will serve as an illustration.

Carbon	Hydrogen	Oxygen	Nitrogen	Ash	Total
57.1	4.6	36.0	0.2	2.0	99.9

Lignite occurs in the Cretaceous and Tertiary formations and often forms considerable beds where these formations occur. It is found in small amount in the eastern United States in the Tertiary at Brandon, Vermont, but in the Cretaceous deposits of the Rocky Mountain States and in the Dakotas it occurs in large and valuable fields. It is found also on the Pacific Coast, and in Germany and elsewhere. Where better coal is not to be had it frequently furnishes a valuable fuel.

Bituminous or Soft Coal. This is a compact, brittle coal of a gray-black to velvet-black color. It has a lamellar, conchoidal, or splintery fracture, sometimes more or less cubical. The luster varies from dull to pitchy; the specific gravity from 1.2 to 1.5. It gives a black to brownish-black streak. It burns with a yellow flame and gives a strong bituminous odor. It often shows distinct stratification through the varying luster of the different layers. Generally there are no traces of organic structures visible to the eye. Some varieties fuse or sinter together on heating, leaving a coherent residue or coke, and are thus called coking coals; others fail to do this and fall to powder. The amount of carbon in a soft coal varies from 75 to 90 per cent. A coking coal from Northumberland in England has been found to have the following composition.

Carbon	Hydrogen	Oxygen	Nitrogen	Sulphur	Ash	Total
78.7	6.0	10.1	2.4	1.5	1.4	100.1

The sulphur in coal is present partly as organic compounds and partly as pyrite, which is a very common impurity. Bituminous coals vary considerably in the relative proportions of fixed carbon to volatile matter, that is, in the proportion of the carbon left behind on heating to the gases, tar, etc., driven off; the latter may be as much as 30 to 40 per cent. Coals containing such a large proportion of volatile matter are called fat coals and are used for the making of gas, coke, etc. Those with 15 to 20 per cent volatile matter are largely used for steam engines and are often called steam coals. They are transitional to anthracite.

In addition to ordinary coal there are, depending on the physical characters, a number of varieties which are well recognized. Thus *cannel coal* is a dull, lusterless, highly bituminous form without structure and generally showing conchoidal fracture. *Jet* is somewhat similar but characterized by its high luster, intense black color, asphaltic appearance, and toughness, which permits of its being readily turned and worked. Its use in mourning jewelry, buttons, ornaments, etc., is well known. It occurs in small, scattered, isolated masses in the later formations in various places, one of the chief localities being Whitby in Yorkshire, England. It is regarded by some as representing water-logged fragments of originally coniferous wood. Bituminous coal occurs in North America in Nova Scotia; in the Appalachian coal field of western Pennsylvania, Ohio, West Virginia, Kentucky, Tennessee, Alabama, and Georgia; the Central coal field of Illinois, Indiana, and Kentucky; in Michigan; the Western field of Iowa, Missouri, Kansas, Arkansas, Oklahoma, and Texas. These are of Carboniferous age. In the Rocky Mountain States and on the Pacific Coast there are also large deposits of Cretaceous and Tertiary age. Elsewhere, in England, Belgium, Germany, France, and Russia, in South Africa, Australia, India, and China, this coal occurs and is mined in quantities. It is the chief coal of the world, and the enormous increase in production in these later years (in the United States from 137,000,000 tons in 1896 to 573,000,000 tons in 1924) points in no uncertain way to its exhaustion in a not distant future.

Anthracite. Hard Coal. This is a compact, dense coal, iron-black to velvet-black in color. It is brittle; has a strong vitreous to submetallic luster, a more or less pronounced conchoidal fracture, and a hardness of 2 to 2.5. Specific gravity 1.4 to 1.8. The amount of carbon in anthracites ranges from 80 to 95 per cent; in Pennsylvania varieties from 85 to 93, and in those of Wales from 88 to 95. The amount of fixed carbon varies from 80 to 90 per cent; the volatile hydrocarbons generally do not much exceed 5 per cent and the remainder consists of moisture and ash. An analysis of a Welsh anthracite is given as:

Carbon	Hydrogen	Oxygen	Nitrogen	Sulphur	Ash	Total
90.4	3.3	3.0	0.8	0.9	1.6 =	100.0

Anthracite requires a strong heat for ignition and with abundant access of air burns with a pale blue flame, giving great heat without smoke or odor. These qualities, with its relative cleanliness, particularly adapt it to household purposes. Some anthracites exhibit on broken surfaces a strong play of spectrum colors produced by iridescent films and are called "peacock" coal.

Anthracite occurs not only in regions of folded strata as previously stated, but also, though usually in no great quantity, where beds containing ordinary bituminous coal or lignite have been invaded by intrusive masses of igneous rock, as in New Mexico, Colorado, Montana, and Scotland. The largest and most important deposits of anthracite are those of eastern Pennsylvania, a considerable part of which has been already mined. It occurs also in Wales, Belgium, France, Russia, and in the province of Shansi in China, as well as in other places.

In addition to the carbonaceous rocks described above, other carbonaceous and sometimes combustible substances occur, such as graphite, ozokerite or mineral wax, asphalt and various modifications of it, petroleum, etc., but not in such a manner or relation that they may be properly included in a work treating solely of rocks. Also, between the coals and the sandstones and shales, intermediate types exist in great variety, but these are best treated under the description of the latter rocks.

H No. 8

Sedimentary Rocks of Mechanical Origin

These include the products of land waste by various erosive agencies, laid down in stratified form by currents of water in seas and lakes, and on the flood plains of rivers, and afterwards consolidated into rocks, as described in the foregoing chapter. According to the size of the particles they are divided into (1) the gravel rocks, or *conglomerates* and *breccias*; (2) the sand rocks, or *sandstones*; and (3) the mud or clay rocks, or *shales*, as previously mentioned.

Conglomerates and Breccias

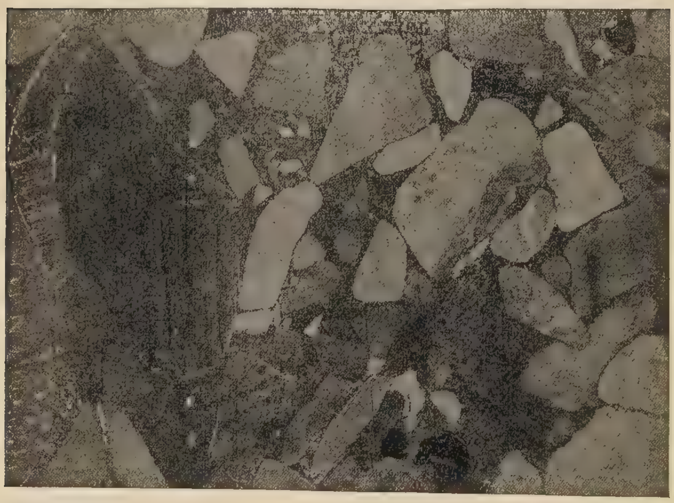
Conglomerates. These consist of pebbles of various sizes, intermingled with a finer material which acts as a cement. The pebbles may vary from the size of a pea up to large boulders. They are rounded by the action of water. They may consist of any kind of rock, though generally of the harder and more resistant varieties, or they may be of a simple mineral, usually quartz or feldspar. The pebbles may be all of one kind or of a mixture of several kinds of rocks or minerals. The cementing material may also vary greatly; it may be composed chiefly of consolidated sand, either purely siliceous or of mixed substances; it may be calcareous in nature, or chiefly composed of clay, or of these substances largely mingled with iron oxide. There may be a sharp distinction between the relatively large pebbles and the very fine matrix in which they are enclosed; and if this contrast is pronounced and the matrix is present in considerable amount, such conglomerates are often called *pudding stone.* On the other hand, there may be gradations in size from the pebbles down into the matrix. There is, of course, great variation in the color of these rocks; in some the pebbles are sharply defined from the matrix by their colors; in others the rock may have one general hue, alike for pebbles and matrix — this is more likely to be the case where the rock has been somewhat changed or altered from its original character.

Breccias. In a breccia the fragments which correspond to the pebbles of a conglomerate, instead of being rounded, are sharp and angular in character. (See Plate 32.) This indicates, if the material has been laid down in water, that they have suffered very little transport and are close to their place of origin. In other respects, what has been said in regard to conglomerates will also apply to breccias.

Conglomerates and breccias, which are composed of a single type of rock, are generally called by its name and we thus have quartzite conglomerates and breccias, limestone conglomerates and breccias, etc. Volcanic breccias, produced by the fragmental accumulations of eruptive

PLATE 32.

A. CONGLOMERATE, OF SEDIMENTARY ORIGIN.



B. BRECCIA, OF SEDIMENTARY ORIGIN.

activity, are really igneous rocks and have already been described (see page 276). The material may, however, fall into water and be rounded, assorted, and stratified, giving rise to *volcanic conglomerates;* such rocks are very difficult, and sometimes impossible, to distinguish from conglomerates formed by the erosion of such land areas as are formed for the most part of lavas.

Breccias are sometimes produced as the result of the breakage and grinding of the rock masses along some fault plane upon which powerful movement is occurring. The fragments thus formed may be afterwards cemented together into firm rock by deposits from solutions circulating in the zone of crushed and broken rock. Such types are called *friction breccias,* or *fault breccias,* and they naturally show no evidence of stratification.

Conglomerates are normally formed from deposits laid down by swiftly moving currents of water which tend to carry away the lighter and finer material in suspension. Hence they represent the deposits of rapid rivers and estuarine currents. Also, when a sinking land surface passes under the sea and the edge of the latter advances, a beach formation sweeps over the land as the initial stage to later deposits. The waves throw the coarser material, the gravel or shingle, toward the upper part of the beach, and as the latter sweeps inland a conglomerate is the first deposit laid down on the new sea bottom. Thus it is general to find a conglomerate or coarse sandstone as the first member of a new series of stratified rocks, resting upon an unconformable lower series, and in thus marking divisions of geologic time conglomerates may be of great importance. They are quite common rocks and are everywhere distributed in the sedimentary formations.

In the older formations and especially in strongly folded mountain regions where the strata have suffered great pressures and shearing, the pebbles of conglomerates are generally distorted and flattened into lenses, or drawn out into spindle-shaped forms. The process is generally accompanied by mineralogical changes which may be especially noticeable in the cement. This is the first stage in the conversion of these rocks into gneisses and schists through metamorphism, as described in the following chapter. On account of their coarse and irregular appearance and inhomogeneous character, conglomerates have been little used for structural purposes, except in the roughest stone work, as in foundations, piers, etc. Some breccias, which are compact and capable of a good polish, have been cut as ornamental stones, as a reddish conglomerate breccia from South Dakota and a vari-colored limestone breccia from Japan. Since the discovery of the wonderful gold deposits in conglomerates in the Rand district, South Africa, these rocks have received much attention, as representing possible fossil placers in which, if the gold has been concentrated by natural processes, available sources of the precious metal might be expected.

Sandstone and Related Rocks

Sandstone. Typical sandstones are composed of grains of quartz held together by some substance acting as a cement. The size of grain may vary from that of peas down to that of fine seeds; as they become finer the rocks pass into shales, just as on the other hand they graduate upward into conglomerates, and thus no sharp line can be drawn between the three kinds. While some sandstones are very pure, consisting of quartz grains alone, others contain intermingled particles of feldspar, garnet, magnetite, tourmaline, flakes of mica, and fragments of other minerals. It can generally be observed with a lens that the grains tend to be spheroidal, and that the larger they are, the more perfect the rounding is likely to be. The general appearance of many sandstones, with respect to their granular texture, is much like that of loaf sugar. As described under quartzite, to which reference should be made, the fracture, in breaking sandstone, takes place chiefly in the cement, leaving the grains outstanding, and this gives the rock its sugary appearance and feeling.

Sandstones differ very much in regard to the cementing material which holds the grains together, and thus different varieties are produced. Sometimes it is deposited silica, sometimes a carbonate — commonly calcite, but on occasion dolomite or siderite, — sometimes extremely fine argillaceous material or clay, and at other times deposited oxides of iron, either reddish (hematite, turgite), or yellowish (limonite).

The colors are very variable, white to gray, buff to dark yellow, and brick-red to reddish brown and brown being common; green, purple, and black are rare. These colors depend largely on the nature of the cement: in the yellow, red, and brown sandstones, oxides of iron predominate; with the other, lighter colors, the material is likely to be calcareous or argillaceous. In addition, the calcareous sandstones are readily detected by their effervescing when touched with acid, while the argillaceous ones give the characteristic odor of clay when

PLATE 33.

A. SANDSTONE, OF FINE GRAIN.

B. LAMINATED SANDSTONE, WITH SLIGHT FAULTS.

breathed upon. The green color is due to glauconite, or sometimes to admixed chlorite. Some varieties appear to be almost devoid of a cement.

Sandstones are usually very porous rocks, and their porosity depends to a large extent upon the amount and character of the interstitial cement. Thus the ratio of the volume of pore space to that of the rock has been found to vary from 5 to almost 30 per cent, the latter being about the greatest amount theoretically possible in deposited sand grains. They average 15 per cent. It is because of this notable porosity that sandstones are the common reservoir rocks from which the oil is obtained in oil fields.

The same characters also condition to a large degree the other physical properties and explain their variations: thus the weight per cubic foot varies from 125 to 150 pounds, the crushing strength from 1500 to 15,000 pounds per square inch. The specific gravity is about 2.6 (2.5 to 2.7), if the rock pores are filled with water.

The chemical composition of sandstone varies considerably; the chief constituent is silica, but the proportions of the other elements depend on the nature of the associated minerals and cement. Some analyses of prominent sandstones used for building purposes are as follows:

	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	K_2O	Na_2O	H_2O	CO_2, etc.	Total
I...	99.4	0.3		...	...	...	...	...	0.2	...	99.9
II..	86.6	8.4	1.6	...	...	trace	2.4	0.7	...	...	99.7
III	92.9	3.8	trace	0.9	trace	0.3	0.6	0.3	1.2	...	100.0
IV .	69.9	13.6	2.5	0.7	trace	3.1	3.3	5.4	1.0	...	99.5
V ..	87.1	3.9	1.3	...	1.1	2.7	1.3	0.8	0.5	1.4	100.1
VI .	90.7	4.6	0.4	0.1	0.1	0.1	0.5	2.8	0.4	0.3	100.0

I, White, very pure Potsdam Sandstone, Ablemans, Sauk Co., Wisconsin; II, Lake Superior Brownstone, Houghton, Bayfield Co., Wisconsin; III, Sandstone, light gray, Berea, Ohio; IV, Brownstone, Triassic, Portland, Conn.; V, Sandstone, Triassic, near Liverpool, England; VI, Bunter Sandstone, Heidelberg, Germany.

The presence of the alkalies points to the presence of feldspar (or mica) in the sandstone; in IV the amount of feldspar must be large, and such a rock is to be classed as an arkose rather than a sandstone.

The structure of sandstones is essentially that of the stratified rocks. They are sometimes thinly laminated and fissile; in other cases they are very thick-bedded and within the individual bed may show a very even texture and be practically free from any evidence of stratification. Sandstones of the latter type are valuable for structural purposes on account of their homogeneous character and capability of being dressed equally easily in all directions; they are often called *freestones.*

These rocks are frequently distinguished according to the character of the cement or admixed material as described above; thus there are *calcareous* sandstones, *argillaceous* sandstones, *ferruginous* sandstones, and *siliceous* sandstones. *Micaceous sandstones* contain considerable muscovite; the tabular flakes are parallel to the bedding and induce a more or less ready cleavage in the rock, giving it a fissile character; the cleavage faces are generally somewhat silvery in appearance from the mica films coating them. *Grit* is a term applied to coarse-grained sandstones in which the particles are, in general, more or less sharply angular, and the cementing material is, as a rule, quite siliceous. They have been considerably used for grindstones and millstones, hence the term "millstone grit." In siliceous sandstones it may happen that the deposited silica is precipitated upon the rounded or angular quartz grains in crystalline position, thus reconverting them outwardly into crystals; examination with the lens shows the crystal forms and faces of the little regenerated quartzes; these are known as *crystal sandstones.*

Green sandstone is a variety full of grains of glauconite which impart a general greenish color to the rock. Sometimes these rocks are very friable, indeed scarcely coherent, as in the Cretaceous formations of the Atlantic border, especially in New Jersey. They are then called *greensand* or, inappropriately, *greensand-marl.* They commonly contain, in addition to the sand and glauconite, iron oxides and fossil shells, either whole or fragmentary. These deposits have been considerably used as fertilizers. Analyses of typical greensands from New Jersey are as follows:

SiO_2	P_2O_5	SO_3	Al_2O_3	$\underbrace{Fe_2O_3FeO}$	MgO	CaO	K_2O	H_2O	Total
34.5	1.2	1.3	6.0	31.5	2.2	2.5	1.5	18.8	99.5
51.2	0.2	0.4	8.2	23.1	2.0	0.5	7.1	6.7	99.4

Arkose. This is a special variety of sandstone in which feldspar grains predominate over those of quartz. Often there is considerable mica present and, if the material is firmly cemented, the rock at a casual glance may closely resemble a granite. The particles are generally sharply angular, and the feldspar tends to be soft and more or less changed to kaolin. Under a lens the irregular, clastic, angular shape of the particles readily distinguishes it from a granite. The mineral composition and the shape of the grains show that the material has been derived from quickly disintegrating granite and has suffered but a very short transport before being deposited. Arkoses often grade into conglomerates and breccias by increasing size of some of the particles. They occur in all of the different geological formations. The red-brown Triassic sandstones of New England are in large part arkose and conglomerate or breccia.

Graywacke. These are sandstone-like rocks of a prevailing gray color, sometimes brown to blackish, which, in addition to the quartz and feldspar of an arkose, contain rounded or angular bits of other rocks, such as fragments of shale, slate, quartzite, granite, felsite, basalt, etc., or of varied minerals, hornblende, garnet, tourmaline, etc. They are in reality impure sandstones and readily pass into fine-grained conglomerates by increase in size of some of the component particles. The amount of cement, as in sandstones, is usually small and it is generally argillaceous, but sometimes siliceous or calcareous. Such rocks, when fine-grained and compact and largely composed of feldspathic material, may be difficult in the hand specimen to distinguish from some felsites, but close examination with a good lens will generally show their clastic character. The name has been rather loosely used and has never had the vogue in America that it has in Europe. Graywacke occurs in the Mariposa formation of the Sierra Nevada, in the Franciscan formation of the California Coast Ranges, and in a belt 1000 miles long, extending along the Alaskan coast from Sitka to Cook Inlet. It is common in Ontario in the Pontiac series of Pre-Cambrian age.

Uses of Sandstone. As is well known, sandstone is everywhere used for constructional purposes. The ease with which it is worked, and the large size of the blocks which may be quarried, make it particularly valuable for this purpose. Thus in the United States a very considerable portion of the buildings of the eastern cities are wholly or in part of the red-brown sandstone, generally called "brownstone," of the Triassic areas of the Atlantic border, while in Great Britain, for instance, the city of Edinburgh is largely built of the Carboniferous sandstones of that region. On account of the insoluble nature of the iron oxide forming their cement, the red and brown sandstones in moist climates retain the details of fine cutting and carving for architectural effects much better than do the lighter-colored gray or buff stones. The latter are likely to have a calcareous cement, which dissolves under the action of atmospheric agencies and water, allowing the stone to crumble, and thus in the course of years the fine details of carving are spoiled. Many examples of this may be seen in the older cities where expensive and beautiful buildings have been much injured. If possible, in building, a sandstone should always be laid with its stratification in a position similar to that which it had in the quarry bed, as it is then much less likely to flake or spall.

Sandstones are of such wide and general distribution in all parts of the world where stratified rocks are found, that it is unnecessary to give any detailed account of their occurrence.

Shale and Related Rocks

Shale is the name given to compacted muds and clays that possess a more or less thinly laminated or fissile structure. The parting is parallel to the bedding, and is the result of natural stratification. When such rocks have been subjected to folding and pressure, they assume a slaty cleavage which does not necessarily coincide with the stratification but may be inclined at any angle to it; they are then slates or phyllites and are described among the metamorphic rocks. This distinction, that rocks showing slaty cleavage are not shales, should be clearly noted, as slates and shales are often confused.

Shales are, in general, too fine-grained for the component particles to be determined with the eye, or even with the lens. By microscopical and chemical analysis they are known to be formed mostly of kaolin and related substances, with which may be associated much white mica, but these are often accompanied by tiny fragments of quartz and other minerals. As the amount of quartz increases, and also the size of grain, the shales pass over into sandstones, and such intermediate rocks represent deposited silts. There are also all transitions between clays and shales, depending on the relative firmness and fissility of the mass.

Clay when dry is a fine, earthy, lusterless mass, giving a characteristic odor when breathed upon. It clings to the tongue, and when strongly rubbed to a powder between the fingers, it finally produces a soft, greasy, lubricated feeling, usually thus differing from loess, adobe, and similar-appearing deposits. It absorbs water very readily and becomes plastic. When pure it is white, but it is generally colored red or yellow by iron oxides, forming the red and yellow *ochers*, or gray, blue, or black by organic substance. The colors are sometimes evenly distributed, and sometimes irregularly blotched, through the mass.

Shales are likely to be soft, cut more or less readily with the knife, and are brittle and crumbly, and these properties, taken in connection with the fissility, often make it difficult to prepare hand specimens of them. Like clays they exhibit a great variety of colors, white to buff or yellow, red to brown, purple, greenish and gray to black, and from the same causes. Different shades of gray are perhaps the most common. They often contain various accessory mineral substances, such as carbonates, gypsum, rock salt, pyrite, etc. Some of these are frequently seen in the form of concretions, which may attain large size, up to several feet in diameter.

Hard, indurated shales that are without fissility or cleavage are termed argillites. Their induration is probably the result of the dehydration and crystallization of the colloidal constituents originally present. Many argillites are distinguishable with difficulty from cherts and felsites.

The chemical composition of shales is somewhat variable, depending on the relative proportions of clay and other minerals. The following analyses will serve to show the general chemical character.

	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	H_2O	XyO	Total
I	55.0	21.0	5.0	1.5	2.3	1.6	0.8	3.2	8.1	1.9	100.4
II	60.6	16.4	4.9	...	1.4	1.6	0.9	3.0	9.7	1.5	100.0
III	61.2	15.6	1.4	3.0	4.2	3.4	0.4	6.7	2.7	1.1	99.7
IV	53.6	17.6	4.1	3.7	5.2	2.3	2.5	2.2	8.5	0.2	99.9

I, Cambrian Shale, Coosa Valley, Cherokee Co., Alabama; II, Cretaceous Shale, near Pueblo, Colorado; III, Devonian Shale, Morenci district, Arizona; IV, Cretaceous Shale, Mount Diablo, California.

XyO = Carbonaceous matter, CO_2, and small amounts of other substances.

There are many varieties of shales, depending chiefly on the presence of accessory materials. Some contain a large amount of organic matter, mostly carbon, and are called *carbonaceous shales*. They are black in color, and by increase of carbon, grade into coaly shales, shaly coals, and so on into coal. They are a very common type, and are found associated with coal and also independently of it, sometimes covering wide areas and of great thickness. From the nature of the organic matter they are sometimes called *bituminous shales*. It is probable that the total amount of carbon in the shales far exceeds that existing in coal beds. The so-called oil shales contain no oil as such but yield oil on destructive distillation. They are now attracting much attention and have enormous potentialities as sources of gasoline and petroleum.

In other varieties of shales large amounts of carbonates, especially calcite, are present, and these are known as *calcareous shales*. By increase of this substance they pass into shaly limestones. They are commonly associated with limestones and these calcareous varieties are detected by their ready effervescence with acids. Again, the carbonate present may be chiefly carbonate of iron and thus produce transition forms between shales and clay ironstone previously described. The connection between clays, shales, and marls has been mentioned on a previous page. *Alum shale* is a variety full of pyrite, or of sulphates resulting from its alteration; it has been used for the manufacture of alum.

Uses of Clay and Shale. The use of clay in the making of bricks, tiles, pottery, etc., is too well known to need comment. Shale has no value for structural purposes, but in recent years, along with clay, it has become of value and is used in many places as a material for the manufacture of Portland cement, when mixed with the proper proportion of limestone and burned. A pure, clean shale or clay of the general composition shown in analysis No. II, given above, is the one best adapted for this purpose, when combined with a non-magnesian limestone.

Clays and shales are such common rocks in all parts of the world where the unmetamorphosed stratified formations are found, that their occurrence needs no special description.

Surficial Deposits

This small group of geologic materials is of somewhat diverse origin, and they are here included under this heading largely as a matter of convenience. They would include æolian deposits, or those made by the wind, and those formed by the disintegration and decay of previously existent rocks. They are appended here to the stratified rocks, because they are in general closely connected with them, and in many cases pass insensibly into them. Many, indeed, which might be classed here wholly or in part, have already been described elsewhere because of their close connection with other rocks. Thus *volcanic tuffs* and *breccias* have been described under igneous rocks; *clays* under shale, *marl* under carbonate rocks, *sands* in Chapter VIII, etc. Most of these substances, in the ordinary usage of the word, would not be considered rocks at all, and their treatment entails matters of geological interest rather than such as enter into a work of this character. This applies to such things, for instance, as soils, talus heapings, morainal deposits from glaciers, etc. Their description and mode of origin should be sought in the handbooks on geology, or in special manuals. Only a few of them, which from their widespread occurrence and great importance as geological formations are of particular interest, are here included.

Loess. This is a deposit of a pale to buff yellow color, running into brown, of an exceedingly fine grain; friable, with scarcely the consistency of ordinary chalk when coherent, and passing into looser forms, and of a rather harsh feeling when rubbed between the fingers. It is of a remarkably homogeneous appearance and commonly shows no signs of stratification, though in places this is clearly seen. Loess consists chiefly of angular grains of quartz, mixed with considerable amounts of clay-like substances, tiny specks of other minerals, and a calcareous cement, the amount of calcium carbonate rising in some cases to 30 per cent. This latter produces an effervescence in acid, which quickly ends. The analysis of a loess from Kansas City, Missouri, may be quoted to show the general chemical composition.

SiO	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	H_2O	CO_2	XyO	Total
74.5	12.3	3.3	0.1	1.1	1.7	1.4	1.8	2.7	0.5	0.4	= 99.8

XyO = minute quantities of P_2O_5. TiO_2. SO_3, MnO and C.

Loess occurs in widespread areas in the valley of the Mississippi, in the states of Ohio, Indiana, Illinois, Iowa, Kansas, Nebraska, Arkansas, Missouri, Tennessee, Kentucky, Alabama, Louisiana, Mississippi, and Oklahoma. It is found also in Europe in various places, especially in the valleys of the Rhine and its tributaries, lying in isolated patches on the upper hill and mountain slopes, and in the same way in the Carpathians. It covers an enormous area in northern central China with thicknesses attaining 1500 to 2000 feet, and the yellow color which it imparts to the Hoang-ho (Yellow River) and eventually to the Yellow Sea, into which the former discharges, gives to these their names.

It is now generally accepted that the loess is an æolian, that is, a wind-blown, deposit of dust which has accumulated through long periods of time. This is shown by its lack of stratification, by the manner in which it lies upon the surface, filling former inequalities, by the remains of land shells which are found in it, and by the small, vertical tubes running through it, caused by the roots and stems of former vegetation. In places, however, where it has been washed down into former lakes, ponds, and streams, it becomes stratified. In America and Europe, the material of the loess is supposed to represent the finely ground rock powder produced by the glacial ice sheet.

A characteristic feature is the common occurrence of concretions of carbonate of calcium and of oxide of iron. They often assume the odd, shapes seen in the flint nodules of chalk. The perpendicular tubules give to the loess a vertical cleavage, which along river banks produces bold bluffs.

Rocks of loessial origin, i.e., lithified loesses, have so far been recognized in but few of the older geologic formations, probably because of the difficulty of distinguishing them. Certain members of the Old Red sandstone of Anglesey, England, have been interpreted as such " dust-rocks."

Adobe. This name is applied to a very fine-grained,coherent, yet friable material which covers wide areas in the semi-arid and arid regions of western North America, especially in the southwestern states and in Mexico. It resembles loess in many ways, usually has the harsh feeling when rubbed between the fingers, and is of a yellowish, yellow-brown, gray-brown or chocolate-brown color. Its use in the form of sun-dried brick for building is well-known. It is the result of the finer detritus of rock decay on the higher slopes of hills and mountains, accumulated on the lower slopes, plains, valleys, and basins, in part by rain wash, and in part by the action of the wind in moving it as dust. It forms a valuable soil when irrigated and brought under cultivation.

Tillite. A till that has become converted into rock is termed tillite. It is generally unstratified and consists of a chaotic assemblage of angular rock fragments that range in size from the finest rock flour to huge boulders. It is therefore likely to resemble a cemented alluvial breccia, or fanglomerate, as it has recently been named. In fact, one can only distinguish tillite from fanglomerate by finding in it faceted and striated pebbles of glacial origin, or by finding that it rests on a glaciated floor. Tillites have now been recognized as occurring in many of the geologic formations, from Pre-Cambrian time onwards.

CHAPTER X

THE ORIGIN AND CLASSIFICATION OF METAMORPHIC ROCKS

Introductory. The metamorphic rocks are those that were originally sedimentary or igneous, but have been changed either in mineral composition or in texture, or in both, so that their primary characters have been altered, or even entirely effaced. Such alteration is termed metamorphism. Here constantly, as elsewhere in geology, gradations exist, and no definite line can be drawn on the one hand between the sedimentary rocks and their metamorphic products, or between the igneous rocks and the metamorphic ones formed from them, on the other. Thus loose chalks pass into limestones, and these into crystalline marbles, just as dolerites merge into greenstones, and so on into hornblende schists, without any sharp line of demarkation. But there comes a point in the change of each original rock, either of composition or of texture and usually of both, where its characters have become so individual that it is best regarded as a distinct kind of rock. In short, metamorphic rocks are those whose distinctive characters have been produced by metamorphism.

Rocks for the most part are composed of minerals, and minerals for the most part are definite chemical combinations, which as a rule are only stable under definite conditions. If the minerals are subjected to new conditions, quite different from those under which they were formed, with new chemical and physical factors operating upon them, they will tend to change into other minerals, that is, to turn into new chemical combinations, which will be those that are most stable under the new conditions. A familiar example is the decay of the feldspar of igneous rocks, and its change into clay and other substances through the action of water and carbon dioxide, as treated under granite. The change in conditions may be so slight that some rock minerals will be able to resist it indefinitely, while others less stable may succumb. Thus igneous rocks, formed by the cooling and crystallization of molten magmas, may remain in the depths for millions of years, and on coming to the surface through erosion and denudation, may be found entirely unchanged, or with only one or two of the constituent minerals altered. At the surface they are at once subjected to new conditions, to the combined effects of changes of temperature, moisture, the various gases of the atmosphere, the products of organic life, etc., and they commence to break up and to form into new compounds. Then their ultimate conversion is only a question of time. The same is true of the sedimentary rocks, only in lesser degree. They are formed of mineral particles, deposited in water and, usually, cemented by pressure and by deposits from solution. While they remain deeply buried and under fairly stable conditions, they are unchanged; when they are exposed to the atmosphere they also tend to change and decay, especially in those minerals that are susceptible.

All these changes that occur at the Earth's surface, however, are not commonly classed as metamorphic ones. For practical purposes all these materials formed by the action of weathering and by the decay of rocks on or near the surface, such as the soils, are not here described. They have been previously mentioned under the foregoing rock types, so far as seems desirable for the object of this work; and only those rocks are treated as metamorphic which, while buried at depth below the surface, have, through the action of certain agencies presently to be described, undergone changes that have practically converted them into new kinds of rocks.

Metamorphic Agencies. The chief metamorphic agencies are mechanical movements of the Earth's crust and pressure, the chemical action of liquids and gases, and the effect of heat. We may simplify these into the effects of movement, water solutions, and heat. All three of these are required to produce complete metamorphism in rocks, though not necessarily all to the same extent, since sometimes one factor is predominant, and sometimes another. Thus in the metamorphism which has already been described as contact metamorphism, induced by the intrusion of a body of magma, the effect of heat is the most important, that of gases and liquids less so, while the effect of movements of the crust, or pressure, is negligible. The rocks produced, however, are actually metamorphic, but for practical reasons they have been given separate consideration, and are not included among those now under treatment. We shall consider the different agencies separately.

Movement and Pressure. Pure, simple, downward pressure, to the amount exerted in the upper part of the Earth's outer crust, appears to have little metamorphic effect. It tends without doubt to consolidate the material of sediments by bringing the grains closer together; but many sediments, although buried under great thicknesses of deposits for geologic ages, on being raised and exposed by erosion without disturbance, such as folding, are found to be practically in unchanged condition.

On the other hand, as commonly supposed, through the gradual contraction of the Earth the outer crust is under compression, and finds relief from time to time by buckling or wrinkling up into mountain ranges. This compressive force, thus acting with lateral thrust, is therefore spoken of as orogenic, i.e., mountain forming. By it whole masses of strata, and possibly included igneous rocks — intrusive, extrusive, and fragmental volcanic — are folded, crushed, and mashed together in the most involved and intricate manner. Not only are the rocks then subjected to vast pressure, but they are subjected also to enormous shearing stresses, which tend to produce forced differential movements among the rock particles. It is particularly this latter effect which is of great potency in producing metamorphism. Its effects may often be seen megascopically by the manner in which large crystals, included pebbles, or fossils are flattened and elongated, or broken into fragments which are drawn out into thin, lenticular masses in the direction of shear. The microscope shows that even minute crystals are broken, and their optical properties affected, as the result of the strain. It is possible, indeed, for this agency working alone to produce rocks having the characteristic outward metamorphic texture, without any change in their original mineral composition, but in combination with heat and water, it is of the highest importance in inducing chemical changes and thereby producing new minerals. It is, moreover, a noticeable fact that so long as the rocks retain their original position, they are unaltered, but as we commence to find them disturbed by orogenic forces, they begin to show signs of metamorphism, and in proportion to the degree to which they have been folded up, mashed, and sheared, they become more and more metamorphosed.

Heat. The effect of heat as a metamorphic agent is very powerful, as is so well shown in contact metamorphism. It increases very greatly the solvent action of solutions; it tends in many cases to break up existing chemical compounds which form minerals, and to promote new chemical arrangements. The heat needed for metamorphism may come from the interior of the Earth, in which the temperature increases greatly with the depth; it may be supplied in part by the transformation of energy resulting from the movements, the folding, and crushing of the rock masses; and in part it may result from intrusions of molten magma, which are very likely to rise and invade the rock masses as they are uplifted and folded.

Liquids and Gases. The chief of these is, of course, water, which under heat and pressure becomes a powerful chemical agency. It acts as a solvent, and promotes recrystallization, and, taking part in the chemical composition of some of the minerals, such for example as micas and epidote, it is a substance necessary to their formation. It is, without doubt, aided also in its action by substances that it may carry in solution, such as alkalies, and by volatile emanations coming from magmatic intrusions, like boric acid, fluorine, etc., as already explained under contact metamorphism. It is this which explains the presence in metamorphic rocks of such minerals as tourmaline, chondrodite, and vesuvianite, which are characteristic of pneumatolytic contacts, and of micas, hornblendes, and other minerals which contain fluorine.

Effect of Depth. The outer crust of the Earth has been divided by geologists into different zones, according to the various geological processes at work. In the outermost one, down to the level at which ground water stands, the rocks are full of fractures, and are exposed to atmospheric agencies — moisture, carbon dioxide, oxygen, etc. Here the rocks tend to decay, to be converted into carbonates and hydroxides, and to form soils. This zone is called the *belt of weathering*, and is the one of rock destruction. Below this lies another, in which the rocks are also full of fractures and cavities filled with water. Its upper level is that of ground water; below, it reaches to the point where the pressure of the superincumbent masses and the contraction of the crust become so great that all fractures and openings are closed up, since the stress is so much greater than the strength of the rocks, that they crush under it, and are to be regarded as being in a relatively plastic state. In this zone the chemical action of water is most important, and is aided by the substances that the water may carry in solution. The tendency is to change the minerals to hydrates, and to a lesser extent to carbonates; thus olivine, an anhydrous silicate, becomes converted into the hydrous silicate, serpentine. Substances are taken into solution and, reinforced by those leached out from the belt above and carried down, are deposited in the pores and fissures of the rocks; hence this zone is called by Professor Van Hise the *belt of cementation*, because the rock-grains are thus cemented together.

Below this lies the zone in which, as stated above, the pressure is so great that all openings are closed up, and the rocks may be regarded as in a plastic condition. Its upper level is variable and depends on geological conditions; in times of quiet it may be twelve or more miles below the surface; in times of mountain making, it may rise much higher than this. Of what may be its lower level, we know nothing. In this zone, the chief agencies are the enormous pressure and the increasing heat of the Earth; the rôle played by liquids and volatile substances is of less importance; the tendency is for them to be gotten rid of, to be squeezed out. The chief work done in this zone is molecular rearrangement, in which less stable mineral compounds are broken up, and new ones of higher specific gravity and smaller volume are formed through condensation. Carbonates are converted into silicates and the carbon dioxide expelled; hydrated minerals have their water driven out, and new minerals, with less or no water, are formed. This zone of rock flowage, in contrast to the zone of fracture above it, has been called the zone of anamorphism by Professor Van Hise. We may term it the zone of *constructive metamorphism.*

It is chiefly in the lower part of the belt of cementation (zone of fracture), and the upper part of the zone of rock flowage, that the greater part of the work of metamorphism, the production of the metamorphic rocks as we see them, is done. In the upper zone, the results are chiefly those produced by shearing and by the imposing upon the rocks of characteristic textures. Chemical work may be done and new minerals produced, but it is possible for new textures to be formed without change in mineral composition. In the lower zone, the work done is largely chemical, new and more stable mineral combinations being formed; and here also characteristic textures are produced.

Minerals of Metamorphic Rocks. Just as certain minerals, of which nephelite and sodalite might be mentioned as examples, are characteristic of igneous rocks, so other minerals, such as *cyanite, zoisite, staurolite,* and *talc,* are peculiar to the metamorphic rocks. Other minerals, such as *quartz, feldspar, amphibole, pyroxene, garnet,* and *mica,* are found in both groups alike. It should be remembered, however, that the names just mentioned are really names of families, under which a considerable number of individual mineral species may be grouped, on account of certain common properties, such as crystal form. Thus in the amphibole group, arfvedsonite is found only in igneous rocks; *tremolite* and *uralite* occur practically only in metamorphic ones; *common hornblende* occurs in both. Of the pyroxenes, the normal home of augite is in igneous rocks; of *wollastonite*, a pyroxene-like mineral of the composition $CaSiO_3$, in the metamorphic ones; of *common pyroxene* in both. Of the micas, *paragonite* has been found only in metamorphic schists, *biotite* and *muscovite* are present in both groups of rocks, but muscovite is relatively rare in fresh, normal, igneous ones. In the garnet group, pyrope, the magnesium-aluminum garnet, is formed only in igneous rocks very rich in magnesium and low in silica, such as the peridotites; it occurs in them, or in the serpentines formed from them, while *grossularite*, the calcium-aluminum garnet, has its characteristic home in metamorphic limestones; *almandite* and *common garnet* are found both in igneous and metamorphic rocks. In the following list are given the minerals that may occur in metamorphic rocks; the first column contains those of wide distribution, and of prime importance, as chief components; the second column, those of lesser importance, which occur either as prominent accessory minerals, or locally developed as chief components; the third, occasional minerals, which may be at times megascopically developed. This is true only in a general way, however, and too much emphasis must not be laid on these divisions.

I	II	III
Quartz	Garnets	Graphite
Feldspars	Staurolite	Tourmaline
Biotite	Epidote	Chondrodite
Muscovite	Zoisite	Vesuvianite
Amphiboles	Cyanite	Hematite
Calcite	Pyroxenes	
Dolomite	Magnetite	
Chlorite	Talc	
Serpentine		

Of these minerals, chlorite, serpentine, and talc are especially characteristic of the upper zone, while cyanite, staurolite, and some of the others are formed in the lower zone. Some minerals, like quartz, and some members of the groups may be formed in either zone, or be persistent components of the original rocks.

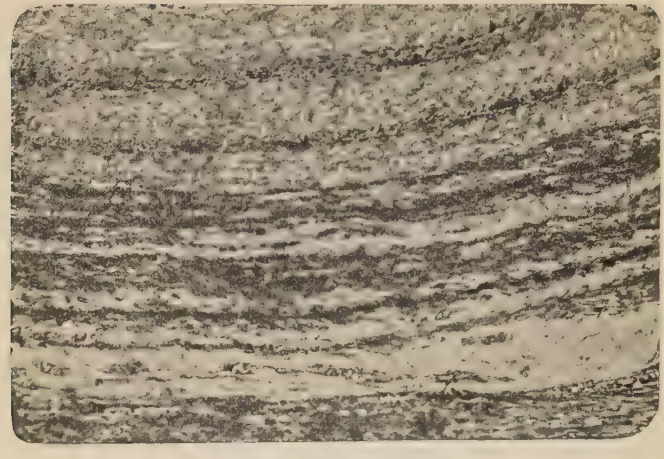
Texture of Metamorphic Rocks. The metamorphic rocks resemble the greater part of the igneous ones in that they possess a highly crystalline character, so much so that they are frequently referred to as the *crystalline schists*. On the other hand, they resemble the sedimentary rocks in possessing a parallel structure which may closely resemble stratification. Thus they show analogies to both of the other great rock groups. This parallel structure expresses itself to a greater or lesser degree by a foliated, laminated, or, as it is frequently termed, a *schistose* texture, one in virtue of which the rock tends to split or cleave more or less perfectly in the direction of a certain plane passing through it. This direction of cleavage is called the *chief fracture*, and the break of the rock at right angles to it is termed the *cross fracture*. Highly crystalline rocks exhibiting foliated texture are called gneisses or schists, according to the coarseness of foliation, as described later. While this is the characteristic texture for the metamorphic rocks, there are a few, such as serpentine, marble, and quartzite, that, for certain reasons to be explained, may not show any trace of foliation, and yet are true metamorphic rocks.

Observation of the gneisses and schists shows that this texture is due to arrangements of unlike mineral grains in layers, or very flat lenses, or to a parallel arrangement of minerals having prismatic or tabular forms, such as hornblende or mica, or to a mixture of both. It is a result of the shearing and pressures to which the original rocks have been subjected, and, under proper conditions, may be imposed upon both sedimentary and igneous rocks alike. The superficial resemblance that the gneisses and schists bear to sedimentary rocks in their parallel laminated character led geologists for a long time to think that the gneisses and schists were derived wholly from sedimentary rocks, and the recognition that they contain metamorphosed igneous rocks as well came only later through petrographic and chemical studies. From the fact that in places sedimentary rocks could be traced into metamorphic ones and the latter into igneous ones, it was even assumed that the igneous rocks were in part derived from sediments by extreme metamorphism. Such cases merely represent instances in which both have been metamorphosed at the same time, with a remnant at either end which is not metamorphosed and whose original characters may therefore be recognized. In the light of our present knowledge we should be no more justified in drawing such a deduction than we should be in reversing it, and deriving the sedimentary rocks from the igneous ones by metamorphic processes!

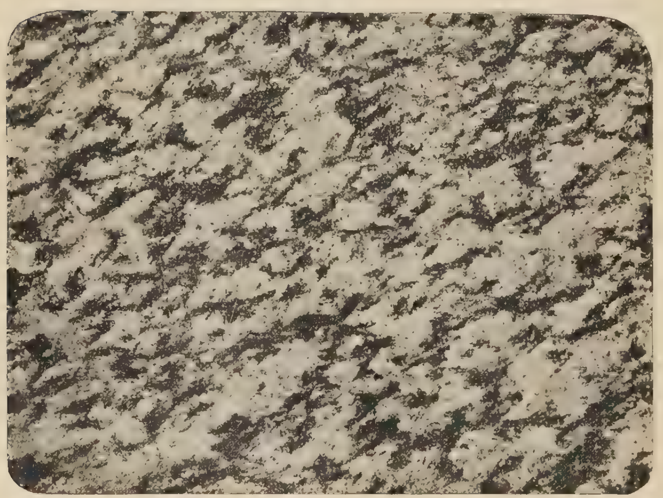
Varieties of Texture. Three chief varieties of foliated texture may be recognized: (1) The *gneissic*, or coarsely foliated. This can be divided into *banded* and *lenticular*. In the *banded*, unlike mineral layers are in parallel bands, as illustrated in Fig. A, Plate 34. This resembles stratification, but may be induced in igneous masses as the result of shear. In the *lenticular*, some of the components are collected into thinner or thicker lenses, around which the other minerals tend to be wrapped or wound, as shown in Fig. B, Plate 34, which shows a view of the cross fracture. The surface of chief fracture here is likely to be more or less lumpy, and not to show well the minerals of the lenses. Both this and the foregoing variety vary greatly from coarse to fine. (2) The *schistose*, or finely foliated, in which the rock tends to cleave into thin flakes or laminæ composed of megascopically visible minerals. (3) The *slaty* texture, in which the mineral grains are extremely small, usually too small to be seen with the eye, and often even with the lens; the rocks appear aphanitic, but they have the capacity of splitting into thin slabs, as seen in roofing slates. The cause of this is discussed under the description of slates.

Metamorphic rocks frequently contain large and well-developed crystals of minerals, which have formed as a result of the metamorphism to which the rocks were subjected. These crystals may be much greater in size than the average grain of the rock, and this contrast, together with the perfection of their crystal form, produces a strong analogy to the porphyritic

PLATE 34.



A. BANDED GNEISS.



B. LENTICULAR GNEISS.
(Maryland Geological Survey)

texture of igneous rocks. These rocks are not true porphyries, however, not only because the texture is not of igneous origin, but also because these large crystals are not of an older generation, but are contemporaneous with the minerals of the apparent groundmass in which they lie, or possibly of somewhat later formation. This texture is therefore termed *pseudo-porphyritic*, or porphyroblastic. These pseudo-phenocrysts, or porphyroblasts, frequently contain as inclusions the other rock minerals; and sometimes the inclusions, such as bits of quartz, graphite, etc., pass through the large crystal in the lines of original stratification, and out beyond it, but this feature can only be seen microscopically. It may frequently be noticed that even though the pseudo-phenocrysts are not equidimensional but elongated, they may lie in the rock pointing in all directions; their longer axes do not necessarily lie in the direction of schistosity, as do those of the other minerals, which have been oriented by the pressure and shearing. Whether a mineral will lie in the plane of schistosity or in random orientation throughout the rock is probably determined by the relative strength of the two tendencies: the inherent directive power of the growing crystal, and the directive effect of the shearing stress simultaneously acting on it. The space in the rock in which movement of material goes on to produce these larger crystals is clearly shown in Plate 35, which is a photograph of a garnet in gneiss. Around the garnet is a zone of feldspar, from which all the ferromagnesian minerals, visible beyond it, have disappeared, having been used up in its formation.

The porphyroblastic crystals should not be confused with larger crystals or crystal masses that may also give the rock a porphyritic appearance, but which are really holdovers from former textures. Such relicts may be former phenocrysts of some porphyritic igneous rock, or large grains from some former coarse-granular igneous rock, or pebbles from a conglomerate. They generally form ovoid masses, and they are then really a pronounced case of the lenticular texture, which is sometimes termed, following the German name, *augen* (eye) *texture*.

Relation to Previous Textures, etc. In proportion to the degree of metamorphism which rocks have suffered, we find that the characteristic textures described above have been imposed upon them. But not infrequently, as though looking through the veil which metamorphism has cast over them, we can see, back of these features, remains of original textures and structures which are characteristic of igneous and sedimentary rocks. Thus, as indicated above, we may see that the original texture was that of a porphyry, or we may find remnants of the spherulites, lithophysæ, and flow lines of some felsite lava, or of the amygdules of some basaltic one; on the other hand, ovoid masses of different mineral composition may indicate a former conglomerate, or parallel layers, differing in general mineral and chemical composition, may show former stratified material. Such indications may be very useful in ascertaining the origin of a metamorphic rock, and sometimes may positively identify it, but deductions from this source should always be made tentatively and used with great caution, for there are many confusing appearances of this kind which may lead to serious error, unless they are checked by microscopic examination and chemical analyses.

Chemical Composition. The chemical composition of the metamorphic rocks is extremely diverse, and it is evident that this must be the case, when one considers the variety of materials from which they may be derived. If we take them together, as a class of rocks, the composition, therefore, cannot have the significance which it has in the igneous ones in showing their mutual relations. It may, however, be of great importance as an aid in helping to determine their origin. Thus, in examining the chemical analysis of a metamorphic rock, we may be able to say that it is similar to that of a known igneous rock and therefore the metamorphic rock was originally of igneous nature; on the other hand, the analysis may show definitely that the metamorphic rock could not have been originally an igneous rock, and consequently it must have been of sedimentary origin.

	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	H_2O	XyO	Total
I...	75.7	13.2	...	1.8	0.4	0.6	2.1	4.7	1.0	...	99.5
II..	50.3	14.1	7.0	5.3	7.2	8.1	4.0	2.3	1.6	...	99.9
III.	74.7	8.9	9.6	...	1.9	1.1	0.4	1.0	1.1	0.5	99.2

I, Gneiss, near Freiberg, Saxony; II, Hornblende Schist (amphibolite), Vestana, Sweden; III, Gneiss, near Rawdon, Quebec.

Thus, in the analyses given above, that of No. I might well be of an ordinary granite, as may be seen by reference to those given under granite; it might also, however, be that of an arkose derived from such a granite. No. II has the composition of a gabbro; it might have been such a rock originally, or a dolerite, or basalt; it does not suggest any ordinary sedimentary rock. No. III on the other hand has no analogy among igneous rocks; the alkalies and alumina are too low for the silica, and the ferric oxide too high; it must be of sedimentary origin and suggests an impure, ferruginous sandstone.

It is inferred, of course, that although movement among the molecules within limited distances has occurred, involving recrystallization and the formation of new mineral compounds, the chemical composition of a rock mass as a whole has remained unaltered. That this is so, is shown by the fact that innumerable sedimentary rocks, although utterly changed in mineral composition from their former state, still retain the original spacing and relative volume relations of the strata. Thus one band in a series of strata, perhaps only a fraction of an inch in thickness, is sharply marked off by its grain, minerals, and texture from those above and below it. There has been no melting and no formal transfusion of substance; consequently the changes which have occurred are, so to speak, internal, those that lie within the range of molecular attraction. To this general statement that there is no change in bulk composition in metamorphism, there is one exception, and that is that volatile substances, liquids and gases, may be driven out and, conversely, new ones may enter and pass into mineral combinations, as previously explained, under the action of liquids and gases as agents. This is most strikingly seen, perhaps, in the metamorphism of impure limestones, as described in the section dealing with marble, and is thoroughly analogous to what has already been stated under contact metamorphism.

Injection of Gneisses and Schists. It has been previously mentioned that part of the heat of metamorphism, and part of the liquids and gases involved in the production of minerals, is supplied by intrusions of igneous magma, which are particularly likely to rise and invade those areas where crustal movements are starting metamorphic agencies at work. In such areas the effect of contact metamorphism merges into that of general metamorphism and no definite line can be drawn between them. Indeed, the earlier-formed intrusions may themselves become more or less metamorphosed, or have metamorphic textures imposed upon them by repetitions of the processes, and this may happen while they are in a solid, or yet partly plastic, condition. There is, however, another function which these magmas, rising under great pressure into rocks already schistose and foliated, may perform; they may insinuate themselves as thin veins, sheets, and lenticles into the schists surrounding them, so that these rocks may become partly igneous, partly metamorphic, in composition. And, as previously explained under contact metamorphism and pegmatite dikes, these effects may be greatly aided by liquid and gaseous emanations from the magma masses. This process has been termed the *injection* of schists by magmatic material and, although it has been doubted by some geologists, just as it has been given entirely too general an application by others, it has undoubtedly occurred in many places. By it we are enabled to understand the veins, stringers, and lenses of granite penetrating the schists in the neighborhood of larger granite intrusions in many places, which would be otherwise incomprehensible. In this connection also, it should be remembered that the intrusive effects in the lower zone of rock flowage may be expected to be quite different from those in the upper zone of rock fracture.

Occurrence and Age. The metamorphic rocks have a wide distribution over the Earth's surface, and in many places they occupy great areas, over which they are the only ones exposed. There is good reason also for believing that they form the basement upon which all the later unmetamorphosed, sedimentary rocks rest. The reason for this is, that wherever these later strata are sufficiently eroded away, this metamorphic basement has come to light. The only exception to this general distribution over the continental areas is in those places where later intrusions of igneous magmas have come up through the metamorphic rocks and are now exposed as batholiths, stocks, dikes, etc. These, however, constitute but a subordinate part of the total area. It is their extension over such wide areas that has given to the processes that have produced them the name of *regional metamorphism,* in contrast to the forming of the small zones around intrusive igneous masses, which is therefore termed *local metamorphism.* There is no difference in principle, however, between these two, but only in the relative intensity with which the varied agencies have operated. The metamorphic rocks are found also in folded mountain ranges, of which they form the interior core, which subsequent erosion brings to light. In proportion to the intricacy of the folding and mashing of the strata, the degree of metamorphism is increased. This is so well established that when we find areas where the rocks are intricately folded and completely metamorphic, but not of any great elevation, we assume that such an elevation formerly existed, but has been eroded away, or in general that metamorphic rocks can become exposed at the surface only through erosive processes.

These facts led to the view, formerly held, that metamorphic rocks must, geologically speaking, be of very great age. This is, however, by no means necessarily the case. For, on the one hand, we find unmodified sands of Cambrian age in eastern Russia, and unaltered beds of Ordovician age in the upper Mississippi valley, which have not been changed from their original position; while, on the other hand, strongly folded strata of Mesozoic and Tertiary age in the Alps, and in other mountains, are in places profoundly metamorphosed. Rocks that are metamorphic are likely to be old, but are not necessarily so, just as a battle-scarred soldier is likely to be a veteran, rather than a recent recruit. It merely depends on whether they have been subjected to metamorphic processes or not, and the older they are, the more likely they are to have suffered from them. Time, however, is one of the great factors in metamorphism, and even in the recent strata that have been changed, the time involved, from our standpoint, is very long.

Classification of Metamorphic Rocks. It would be natural to classify the metamorphic rocks according to the origin of their material, and to separate those of igneous from those of sedimentary formation. In some cases this may be done. Thus it is clear that marble is not of igneous origin; but when we attempt to carry this principle through, it quickly becomes impracticable, especially if we can use only megascopic means of determination.

SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	H_2O etc.	Total
69.9	13.1	2.5	0.7	trace	3.1	5.4	3.3	1.0	99.0
69.9	14.9	1.8	0.6	0.6	1.5	5.3	3.9	1.3	99.8

Thus, in the two analyses given above, the upper one is that of the Portland sandstone of Connecticut, a fine-grained arkose full of feldspar, the lower one that of an intrusive granite porphyry from the Crazy Mountains, Montana. It is evident that if these two rocks, one sedimentary, the other igneous, should be so thoroughly metamorphosed as to lose all traces of their original textures, it would be impossible to discriminate them from one another, or to say what their original status was.

On the basis of the simple primary classification of the sedimentary rocks previously given, it is possible, in a very general way, to show the relation between the most common ones and their metamorphic derivatives in the following table:

Sediments	Sedimentary Rocks	Metamorphic Rocks
Gravel...............	*Conglomerate*.......	*Gneiss, and various schists*
Sand.................	*Sandstone*...........	*Quartzite* " " "
Silt and Clay.........	*Shale*...............	*Slate* " " "
Limy deposits........	*Limestone*..........	*Marble* " " "

In the case of the igneous rocks, recalling that they may be roughly divided into two main groups, the one chiefly feldspathic, and the other mainly of ferromagnesian minerals, we can illustrate also, in a very rough and general way, the relation between them and their metamorphic derivatives in the following table:

Igneous Rocks	Metamorphic Rocks
Coarse-grained feldspathic types, such as *granite*, etc.	*Gneiss.*
Fine-grained feldspathic types, such as *felsite*, *tuffs*, etc.	*Slate* and *Schists.*
Ferromagnesian rocks, such as *dolerites* and *basalt.*	*Hornblende, Talc,* (etc.), *Schists* and *Serpentine.*

A comparison of the two tables will show that gneisses and schists may have diverse origins, and the reason for this has been previously pointed out.

Another method of classification, which has been developed chiefly by the Swiss geologist, Grubenmann, disregards the origin of the material entirely and considers only its chemical composition. According to this the metamorphic rocks are divided into groups. The Earth's crust is divided vertically into three zones, somewhat as described above, and the effect of the metamorphism in these depth zones upon each group is considered. It is found that material of a given composition yields rocks that differ in mineral composition and texture according to the zone in which the metamorphism occurred. Thus the first grouping is a chemical one, while the subdivisions are mineral and metamorphic, and in this way the different rocks are classified. The concepts underlying this classification by depth zones have proved exceedingly fruitful, and by analogy have been applied by Lindgren to the study of ore deposits, where they have proved equally fruitful.

While this method may be consistent and based on scientific principles, it is not a practical one for field and megascopic use. We cannot make analyses of rocks under ordinary circumstances, nor can we, in most cases, even estimate megascopically the chemical composition from the minerals they contain, as can be done with the microscope and thin sections.

At present we are obliged, for practical purposes of field work and megascopic determination, to classify the metamorphic rocks quite arbitrarily according to their evident mineral composition or texture, or a combination of both. Stress may be laid upon the first feature, or, as in the slates, upon the second one, whichever is the more evident and characteristic.

We have, in agreement with this, the following main groups of metamorphic rocks

Grouping of Metamorphic Rocks

1. *Gneisses.*
2. *Mica-schist* and *Quartzite.*
3. *Slates* and Phyllite.
4. Talc and Chlorite Schists.
5. *Amphibole Schists.*
6. *Marble,* Calcium carbonate-silicate Rocks.
7. Dolomite, Magnesium carbonate-silicate Rocks.
8. *Serpentine.*
9. Iron oxides and other rocks.

By comparison it may be seen that the above is in the main a combination of the two tables previously given. The more important of the members are given in italics.

CHAPTER XI

DESCRIPTION OF METAMORPHIC ROCKS

Gneiss

The term gneiss is used to denote a rock of a coarsely foliated texture. Thus when we say granite gneiss, syenite gneiss, diorite gneiss, we use it to denote rocks having the composition indicated by the first word and the texture indicated by the second. The only general definition of gneiss sufficiently broad to cover all the varieties to which the term gneiss is applied is that it is a coarse-grained, roughly foliated rock.

Mineral Composition. Various kinds of *feldspar* may occur in gneisses, both the alkalic and the soda-lime varieties, but they can rarely be distinguished by megascopic means. The feldspars are white to gray in color, or reddish, as in granite, and are generally in more or less round, or elongated, lenticular grains; this lack of definite form makes it more difficult to distinguish them from the quartz than in most granites, and consequently the cleavage should be carefully sought. Sometimes large grains, the size of a pea, or even larger, occur, giving the gneiss a porphyritic character; if the cleavages of these are examined against the light, it may often be observed that they are Carlsbad twins. Such large crystals may indeed have been the phenocrysts of a former porphyritic granite, or they may have been feldspar pebbles of a conglomerate or arkose, or they may have been made by injected material.

The *quartz* is also in more or less round grains or lenticular masses, or in granular aggregates with the feldspar. Its color is white or gray, sometimes reddish, rarely bluish. In the larger grains it is easily recognized by its glassy luster and conchoidal fracture.

The *mica* may be either biotite or muscovite, or a mixture of both. The biotite is black or dark brown, the muscovite is white or yellowish to light brown, sometimes pale green. The mineral does not have any distinct crystal form, but is in flakes, shreds, or irregular leaves, drawn out in bands, or in thin patches. It usually lies stretched out along the structure planes of the rock; and in large part its easy cleavage, thus arranged in one direction, conditions the foliation of the rock, and gives emphasis to the gneissic texture. Thus the surface of easy fracture of the gneiss may appear to be largely coated with mica, and, judging from this alone, one would be likely to form an exaggerated idea of the relative amount of mica in the gneiss; the surface of cross fracture should also be examined to gauge correctly the amount of mica, as compared with the other mineral constituents. This seeming predominance of mica is also especially common in the mica schists and in those gneisses that by increase in their content of mica form transitions into the mica schists. This effect is also more marked in many gneisses, because there is a tendency for the quartz and feldspar to occur in layers, which alternate with layers of mica.

Hornblende may occur in gneisses, sometimes associated with the mica, sometimes alone, forming a special variety. It is seen in dark, prismatic crystals without good terminations, as in granite, syenite, etc. Minute crystals may be aggregated into flattened lumps and layers.

Besides these, many other minerals may occur in gneisses, sometimes so prominently as to form special varieties. Of these *garnet*, of a dark red variety composed largely of the almandite molecule, is perhaps the most conspicuous. The crystals are sometimes large, as compared with the size of the other constituents. *Epidote* may also be discovered, as well as *graphite*, in some varieties. *Sillimanite*, a mineral with the same composition as andalusite and cyanite, is sometimes seen in gneiss, in bundles and brush-like groups of slender fibers or prisms. *Tourmaline* occurs in notable quantity only where the gneisses have been subjected to pneumatolysis. In some gneisses the mica may be partly, or wholly, replaced by *chlorite*, usually from alteration.

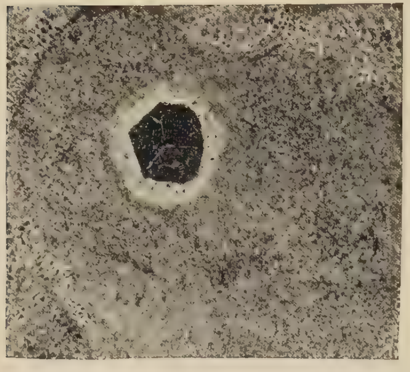
Texture. This has already been described in large part in the general remarks on metamorphic rocks and what has been said above respecting the mica. The essence of the gneissic texture consists in the layers of mingled quartz and feldspar, which are separated by films or layers of platy and columnar minerals, commonly mica or hornblende. Where the amount of mica or hornblende is small, the gneissic texture is less evident, and it increases with the increase of mica. Sometimes these layers are thick and coarse, giving a pronounced banded effect; sometimes they are extremely thin. In some gneisses the layers continue their individual character for considerable distances; in others they are very short and lenticular. According to these appearances, different varieties of gneiss have been named on a textural basis. The gneissic texture is sometimes scarcely perceptible in a hand specimen, but clearly seen on a large exposed surface of the rock. This is especially true in rocks which were originally granites, but which, by pressure and shearing have been converted into gneiss.

The banding may extend for long distances in straight, regular lines, or it may be curved, folded, contorted, or faulted, often in the most complex and remarkable manner, and on any scale, even to a very minute or even microscopic one. Examples of such intricately folded gneisses are seen on Plates 35 and 36.

In some gneisses, as in some granites, a definite *porphyritic* texture may be present, with large and definite crystals of feldspar, which show more or less distinct crystal form.

Such gneisses are to be generally regarded as originally porphyritic granites, which have had the gneissic texture imposed upon them, though it is possible that the large crystals in some gneisses have been formed by growth from injected material. Such gneisses are allied to, and may pass over into, types that, with a short, thick, lenticular texture, contain ovoid masses of feldspar or quartz. The ovoid bodies are called "eyes" (German, *augen*), and the rocks containing them "augen gneiss" from the German name, or "eyed-gneiss." As explained on a previous page under the texture of metamorphic rocks, the augen may be of quite diverse origins.

PLATE 35.



A. GARNET IN GNEISS, WITH ZONE OF GROWTH.

B. GNEISSOID CONTORTED SCHIST.

(U. S. Geological Survey.)

In some gneisses are to be seen pebbles of various kinds of previously existent rock masses, of granite, quartzite, etc. They are generally drawn out into flattened lenticular masses, but their original character is evident, and it is clear that the gneiss was originally a conglomerate, the finer material of which has been metamorphosed, leaving the larger pebbles mostly unchanged, save in shape.

The so-called " primary gneisses " are mainly granites that have a foliation as the result of magmatic flowage during consolidation: by this flowage the earlier-formed minerals, especially the biotite, assume a parallel arrangement. Such gneisses are not metamorphic rocks at all. More and more of the gneisses are being shown to belong to this class.

Color. The color of gneisses is too variable a feature to be of any value as a special character. It depends on the color of the quartz, feldspar, and other minerals, and on the relation of these to the amount of biotite or other dark-colored minerals that the gneiss may contain. Also, in gneisses of sedimentary origin, carbonaceous material may be present, and in the form of graphitic material may color the rock very dark. Hence we find the color of gneisses varying from almost white through light shades of red or gray into darker ones, into brown and green, and even black.

Chemical Composition. As the sources of the material from which gneisses have been made are various, we find great variability in their chemical composition, so much so that this character is not one of their distinctive features. Since many of them are composed of quartz and feldspar in notable amount, such gneisses must contain silica, alumina, and alkalies, and they usually have also more or less iron and lime, but these oxides may vary within wide bounds. The following table gives analyses of a few typical gneisses.

	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	H_2O	XyO	Total
I...	71.0	15.0	1.1	1.8	0.7	0.3	2.5	5.8	1.1	0.5	99.8
II..	65.1	16.4	0.9	5.6	2.4	2.4	3.3	1.9	0.7	1.3	100.0
III.	78.3	10.0	1.8	1.8	1.0	1.7	2.7	1.3	1.0	0.9	100.5
IV .	82.4	11.3	1.0	0.3	0.2	0.2	0.6	1.0	2.5	0.2	99.7
V ..	52.2	18.8	2.7	5.3	5.1	8.0	3.3	1.6	1.4	1.7	100.1
VI .	44.5	17.5	3.4	12.6	5.7	3.3	3.6	3.5	1.6	5.2	100.9

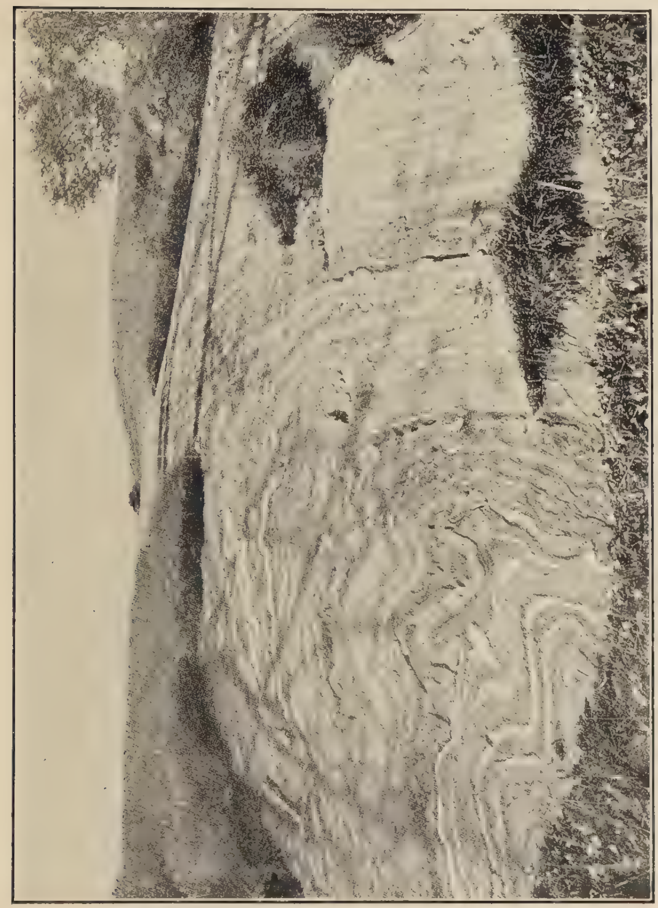
I, Granite Gneiss, Lincoln, Vermont; II, Garnet-biotite Gneiss, Fort Ann, Washington Co., N. Y.; III, Gneiss, fine grained, Great Falls of Potomac River, Md.; IV, Schistose Gneiss, Marquette region, Michigan; V, Plagioclase Gneiss, Mokelumne River, California; VI, Gneiss (Kinzigite), Schenkenzell, Black Forest, Baden.

Nevertheless, as stated in the introduction to metamorphic rocks, the analyses may suggest a clue to the origin of the gneisses. Thus analyses III, IV, and VI above are quite unlike those of any igneous rock, and are almost certainly of material of sedimentary origin, while the others may be of igneous derivation.

Varieties of Gneiss. A very great number of varieties of gneiss have been distinguished by geologists and petrographers. These ~~have been~~ based partly on differences in texture, such as "banded gneiss," "lenticular gneiss," "augen gneiss," etc.; partly on the presence of some characteristic or unusual mineral, such as "biotite gneiss," "hornblende gneiss," "epidote gneiss," etc.; and partly on general composition, such as "granite gneiss," "diorite gneiss," etc. In the latter case the term gneiss, as explained in the introductory paragraph, is used in the sense of a general textural modifier. It would not be suitable in a work of this kind to give a description of all these varieties, but a few of the most prominent may be mentioned. The textural modifications have already been sufficiently considered under the heading of texture.

Of mineralogic varieties, by *common gneiss*, or "gneiss" for short, *mica gneiss* is meant. If further distinction is required, the kind of mica present may be stated, and we thus have *biotite gneiss*, *muscovite gneiss*,

PLATE 36.



CONTORTED GNEISS, OTTAWA RIVER, CANADA.

(After R. W. Ells.)

or *biotite-muscovite gneiss.* If the mica is accompanied or replaced by some prominent mineral, as often happens, other varieties are formed, such as *hornblende gneiss, epidote gneiss, tourmaline gneiss, garnet-biotite gneiss,* etc. The different prominent minerals, which may thus take part, have already been described under composition. Of the varieties based on general composition, it may be said that all of the different varieties of coarser-grained, feldspathic, igneous rocks may occur with pronounced gneissic texture. In accordance with this we have *granite gneiss* — by far the most common variety — *syenite gneiss, diorite gneiss,* and even *gabbro* and *anorthosite gneisses.* Sometimes this texture has been imposed upon the igneous rocks after they have solidified, by intense pressure and shearing, and sometimes while they are still soft, pasty and crystallizing, by magmatic flowage, as already mentioned.

Inclusions in Gneiss. It is very common to find, embedded in gneiss, inclusions, or smaller rock masses, which differ in a marked degree in mineral composition, texture, etc., from the main rock body which encloses them. Thus lenticular masses of *quartz* frequently occur, and are of very variable size. They may be the remains of a quartz pebble of a conglomerate, as explained under texture, or they may have been deposited from solution in some lenticular cavity, opened in the folding of the rock masses. Such occurrences may sometimes be detected by the tendency of the quartz mass to possess a comb structure, composed of an aggregate of crystals whose prism directions are set perpendicular to the wall of the cavity. In many gneisses irregular spots, streaks, and lines of *pegmatite* occur, similar to those in granite. In addition to the quartz, feldspar, and mica, they often contain the accessory minerals seen in granite pegmatite dikes, such as tourmaline, apatite, beryl, garnet, topaz, etc. In the latter case they probably represent the remains of former granite pegmatite dikes, which have been folded up or squeezed out in dynamic metamorphic processes; but not all of the pegmatitic modifications seen in gneiss are to be certainly ascribed to such an origin, for they may have been produced by secretions from later solutions of heated waters moving through the rock mass. The beautiful crystals of orthoclase, of the varieties called adularia and moonstone, occurring in some gneisses, have probably been produced in this way.

Also there are frequently seen in gneiss, spots, streaks, and irregularly curved and winding ribbons of white or pink fine-grained granite similar to the aplite of granites. These may be aplite dikes that have been folded after intrusion, or later granitic intrusions or secretions from heated solutions. They are sometimes seen in the most complicated systems of network passing through the rock, and they may not have any definite wall against the gneiss, as in regular aplite dikes. By their foldings, faultings, and contortions, they often show very clearly the movements that the general rock body has undergone.

Included masses of other kinds are also frequently met with in gneiss. Thus the streaks and smears, produced by aggregates of the dark-colored or ferromagnesian minerals, such as are seen in granites and are described as " schlieren," are found in gneiss, and may have a similar origin. Also, irregular masses, strips, and lenticular bodies of other schists occur, which, if the gneiss has been derived from a former mass of igneous rock, may have been included or enveloped fragments of the stratified beds into which it was intruded.

While the study of thin sections under the microscope is often of great assistance in the field study of a gneiss, in the endeavor to ascertain its origin and thus to understand better its relation to other rocks, it is by no means always necessary. Very much may be done by careful observation in the field of all the facts ascertainable, and by the thoughtful correlation of these facts with one another. From place to place the rock should be minutely studied with the lens and any change in mineralogical composition or texture noted. The following statements embody some of the chief points that should be looked for, to distinguish gneisses originally igneous from those of sedimentary origin. The igneous ones are more likely to have a uniform composition and texture over large areas. The region of the contact with other rocks should be carefully observed, to see if there are any remains of a former endomorphic contact visible, such as a diminishing of grain, or the assumption of a porphyritic texture, as well as the appearance of pneumatolytic minerals, of which tourmaline may be cited as a specially important example. The remains of former aplite dikes and pegmatite veins, as described above, should also be noted in this connection. The enveloping or bordering rocks should be carefully studied to see if, by change in mineral composition, in texture, and in the presence of tourmaline, or other pneumatolytic minerals, any remains of a former aureole of contact metamorphism may be discovered. The character of the plane of contact of the gneiss and its neighboring rocks should be examined to see, if possible, whether they are interwoven, as contorted interlaminated beds might be expected to be, or whether the gneiss cuts directly across them. In fact, all of the field characters indicative of intrusion, which have been described under granite, should be looked for under the veil which metamorphism has cast over the region under study. They may, of course, have been entirely obliterated, but some of them may persist and be valuable indicators.

In sedimentary gneisses, on the other hand, more rapid changes in composition and texture may be looked for, from place to place, both on a large and on a minute scale. The remains of former pebbles, or small, lenticular masses of different composition indicative of pebbles, should be sought for. The presence of carbonaceous matter, or graphite, diffused through the rock, or collected in spots or streaks, is also of use in indicating a sedimentary origin. The absence of any of the signs of intrusion, and the character of the contact, as mentioned above, may likewise be of value.

If, to the facts observed in the field, a chemical analysis of a well-selected specimen, or series of specimens, of the gneiss can be added, this may prove to be of great value. This has been commented on elsewhere and need not be repeated.

When all is said and done, however, it must always be remembered, as Rosenbusch, the great German petrologist, has well said, that " there is no formula by which the derivation of a gneiss may be invariably determined." It must not be done on any one character alone, but all must be taken into account and relatively balanced, and even when this is done, it is impossible in many cases to say whether the gneiss has been derived directly from an igneous rock, or whether the material of the latter may not have passed through an intermediate sedimentary stage.

General Properties and Uses of Gneiss. Those gneisses, that under the action of metamorphic agencies have been thoroughly recrystallized, form solid and massive rocks, the general properties of which closely resemble those of the massive igneous ones. Thus granitic gneiss closely resembles granite, and is used in the same manner for building and structural purposes. But often gneiss contains so much mica that it has too marked a foliation to be of much value. In general a gneiss should be so placed that the plane of easiest fracture lies in the mortar bed with the cross fracture exposed; otherwise it is likely, like some sedimentary rocks, to split and scale badly. Those gneisses that have assumed their texture under conditions of dry crushing and shearing are very tender and friable rocks, which fall to pieces readily under the blow of the hammer, and are of little value. The granite gneiss of portions of the Alps, and the anorthosite gneiss of parts of the Adirondacks, are examples of this. The jointing, erosion forms, etc., of granite gneiss are similar, in general, to those described under granite. So also is the weathering, and gneisses form fertile sandy soils which pass into loamy ones, as the decay of the feldspar and its alteration into kaolin becomes more complete.

Occurrence of Gneiss. Gneiss, especially common or mica gneiss, is one of the most common and widely distributed of rocks. The occurrence of the metamorphic rocks in general has been already commented on, and it was stated that they form a basement in mountain regions and in those areas where the sedimentary beds have been eroded. In such places common gneiss is usually the most prominent rock. Owing to this, it is spoken of by many geologists as " the basal gneiss," or " fundamental gneiss," and as, in many places, it is clearly the oldest rock of which we have any knowledge, some thought that they saw in it the primitive crust of the Earth. The Pre-Cambrian rocks of many regions are almost entirely composed of gneiss, and to attempt to mention all the localities of the rock would be practically equivalent to a description of the occurrence of the Pre-Cambrian. Gneisses are not of course restricted to the Pre-Cambrian; they occur in later formations, into the Mesozoic. Gneisses are found all over New England, and southward along the Piedmont plateau into Georgia; in the Adirondacks; in the Rocky Mountain region, and other places in the United States; they cover large parts of eastern Canada and are prominent in Scotland, Norway and Sweden, Finland, parts of Germany, and in the Alps. In all of these regions different varieties, such as hornblende gneiss, are associated with the common kind.

Granulite. Associated with gneisses in a number of localities is a schistose, to thin schistose, rock composed almost wholly of quartz and feldspar. It is nearly, or wholly, free from mica, and is usually of fine to minute grain, so that, except for its schistose character and place of occurrence, it is much like an igneous felsite or aplite. It commonly carries minute red garnets, and sometimes small quantities of other minerals, such as cyanite, tourmaline, or hornblende, can be detected with the lens. Chemically, it is similar in composition to some felsites or the aplite variety of granite, and it probably represents in general former igneous rock of this nature which has been involved in the metamorphic processes. Such granulites occur in Saxony and other places in Germany, where they were first studied; in Sweden, Finland, Austria, etc.; in New England and in the Adirondack region of New York.

Mica Schist

Mica schist is a rock that is closely related on the one hand to gneiss and on the other to quartzite. It is not only a very common companion of gneisses, in regions of metamorphic rocks, but in many places gneiss grades into mica schist, so that no definite line can be drawn between them. Mica schist has many other analogies with gneiss, some of which will presently be mentioned. Of that great class of rocks known as schists, it is the most widely distributed and important.

Composition — Minerals and Texture. The essential minerals of mica schist are quartz and mica, and it is especially the latter which gives the rock its particular character. Different varieties of mica occur; the most common is a silvery white muscovite; biotite of a dark color is common, while the sodium-bearing mica — paragonite — is rare. Muscovite and biotite occur alone, and also in combination, as in gneiss. The micas are in irregular leaves or tablets, without crystal boundaries, or in leafy or foliated aggregates; biotite and muscovite are found intergrown, and often so that they have a common cleavage. The micas lie with their cleavage planes in the direction of schistosity, and it is this feature that produces the extraordinary fissile character of the rock. They are also very often curved, bent, or twisted, as may be easily seen by the reflections from their cleavage surface. The cleavage of the mica is so marked that the surface of chief fracture, or the schistose plane of the rock, appears completely coated by mica, and the impression may be produced that mica is the only mineral present; to see the quartz, the other essential component, the cross fracture should be examined with the lens. The quartz forms irregular grains, or aggregates of grains, and these are sometimes arranged in small lenses, and sometimes in thin layers, concordant with the layers of mica.

Mica schists, while they are very often composed of these two minerals alone, also very commonly carry crystals, often of large size, of other minerals. The most common of these is a dark red garnet, sometimes sparsely, but generally thickly, sprinkled through the rock, and varying in size from that of coarse shot to that of a plum. These garnets are often in the form of simple, rounded nodules, but as a rule they show more or less distinct crystal form, and sometimes they are beautifully crystallized in the shapes mentioned in the description of this mineral. This garnetiferous variety of mica schist is a very common metamorphic rock.

Other minerals that occur in mica schist in a manner similar to garnet are staurolite, cyanite, epidote, sillimanite, and hornblende. These sometimes are in large and well-formed crystals, which, especially staurolite and cyanite, are not infrequently colored dark by included carbonaceous matter. Graphite occurs in some mica schists in quantity sufficient to produce a distinct variety. Graphite is such a strong coloring matter that a relatively small amount will cause the rock to appear as if almost entirely composed of it; in consequence unsuccessful attempts have been made in places to exploit such lean schists for graphite.

Hornblende, when it occurs, is in dark-colored prisms; by its increase in amount transitions into amphibolite or hornblende schist are formed.

Cyanite, sillimanite, and staurolite occur in prismatic crystals, which may attain a length of several inches. Their formation is contemporaneous with the metamorphism of the rock, and they produce a pseudo-porphyritic texture as previously explained on page 357. Another variety of mica schist is one that contains more or less calcite mingled with the quartz; it is readily detected by its effervescence with acids. This variety commonly contains accessory garnet, epidote, hornblende, etc.

The parallel texture of the rock is its especial feature, and its ready fissility is produced by the mica. If the components are in thin, parallel layers, the surface of rock cleavage is smooth and flat; if the lenticular arrangement of the quartz is prominent, the surface is uneven or lumpy. Frequently the surfaces of schistosity are bent, folded, and crumpled, showing pressures and shearing secondary to its production.

Chemical Composition. As in the gneisses, the chemical composition of these rocks is too variable a feature to be of specific value. This comes from the natural variability in the composition of the sediments from which most of them are formed. It is clear, however, that they must contain silica, alumina, and potash to form the quartz and mica, and also magnesia and iron, if biotite is present. The excess of magnesia over lime, taken with the high silica, is a character foreign to igneous rocks and is clearly indicative of sedimentary origin. Mica schists are probably formed mostly by the metamorphism of argillaceous rocks. Two analyses of typical samples carried out in the laboratory of the United States Geological Survey are here appended.

SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	H_2O	XyO	H_2O
64.7	16.4	1.8	3.8	3.0	0.1	0.1	5.6	3.1	0.8	99.4
64.8	14.4	1.8	4.5	2.3	2.3	1.4	5.0	2.0	1.9	100.4

General Properties. The *color* of these rocks varies from very light, through gray, yellow, or brown tones, into very dark, depending on the proportions of light and dark mica, the presence of carbonaceous material, and in part on the amount of alteration of the iron-bearing biotite. Some pure muscovite schists are almost silvery white or light gray. The hardness and firmness of the rock depend on the proportion of mica; the more of this is present, the softer and more easily cleavable the rock is. For this reason mica schists are of little or no value for practical purposes. *Inclusions* of various kinds occur in mica schists as in gneiss; thus veins and lenticular masses of quartz, deposited from solution in cracks and cavities opened by movement and foldings of the rocks, are common. They also contain in places lenticular masses of other schists, which may vary from very small to huge dimensions. Sometimes they are penetrated by seams and patches of granite, aplite, and pegmatite as the result of granitic injections. With respect to the *alteration* of mica schist, the varieties composed of muscovite are chiefly mechanically disintegrated by the action of weathering without much chemical change. The muscovite resists alteration energetically, and the gravelly or sandy soils formed are in consequence filled with its sparkling flakes. Where much biotite is present it alters easily; the rocks turn yellow or brown, lose their luster, and eventually much limonite is separated out.

Varieties and Occurrence. The varieties composed chiefly of muscovite, or with associated garnet, are the most usual kinds, and are found all over the world as common rocks in metamorphic regions. They are generally associated with gneisses. They cover large areas in New England and extend southward to Georgia. Biotitic varieties are also very commonly found with them. Staurolitic mica schist occurs in many places in New England, and in Maryland, and elsewhere along the Piedmont plateau; it is found in Scotland and in various localities in Europe, in Brazil, and elsewhere. Cyanite-mica schist occurs in various places in New England; a variety in which the mica is paragonite comes from the St. Gotthard region in the Alps, and is seen in mineral collections on account of the beautiful crystals of cyanite it contains; the common kind with muscovite is found in many places. Hornblendic mica schists occur as included lenticular masses, often of large dimensions, in various places, in the ordinary mica schists. Graphitic mica schist is found in Connecticut and other places in New England, in various localities in Germany, Norway, etc.

An interesting variety is conglomerate-mica schist, which contains pebbles of quartz, granite, and other rocks that are very likely to be flattened, lenticular, or drawn out by the pressure and shearing to which they have been subjected. It is closely related to the conglomerate gneiss previously described and is of similar origin. Such rocks occur in Massachusetts, in Vermont, Scotland, Sweden, etc.

Transitions and Relation to Other Rocks. The gneisses formed from sediments and the mica schists have been made from similar rocks: from feldspathic sandstones, shales, and conglomerates. During the transformation to mica schists the feldspar has been converted into mica; in the gneisses it has mostly persisted or been recrystallized. It is not intended in this statement to affirm that this is the only origin for mica schists, only that it is the most usual one; some have been formed from quartzose feldspathic igneous rocks. In this connection what is said elsewhere of phyllites should be consulted. On the whole it is most probable that the gneisses have been formed, as a rule, from the conglomerates and coarser-grained sandstones, the mica schists from the finer-grained ones and from the shales, though many exceptions must occur.

It is therefore easy to understand that no hard and fast line can be drawn between gneisses and mica schists, as previously stated. The decision as to whether a given rock should be classed as a gneiss or a mica schist is often purely a matter of choice; in general, if the amount of mica is large and the rock is thinly foliated, it is best to classify the rock as a mica schist; if the amount of mica is small, the texture coarse, and the foliation imperfect, it is best to define the rock as a gneiss.

On the other hand, in proportion as the original sandstones were more and more purely composed of quartz grains there would be less and less of mica made during metamorphism, and in this way formal transitions into quartz schist and quartzite are produced in their metamorphic representatives. We thus see that gneiss, mica schist, and quartzite form a graded series in which the divisional lines must be purely arbitrary.

Again, as mica schists become finer and finer in grain and in texture, they pass into micaceous slates and so on into slates, and this becomes more marked if the amount of carbonaceous matter increases, as it tends to mask the mica. The divisional line thus becomes an arbitrary one in this case also.

Quartzite

Quartzite is a firm, compact rock, composed of grains of quartz sand united by a cement of subsequently deposited quartz. It is in general a metamorphosed sandstone, and while no hard and fast line can be drawn between sandstones and quartzites, since all degrees of transition can be found between them, the quartzites are much harder and firmer than the sandstones. The sandstones have a more or less sugar-granular feeling and appearance; the individual grains are distinctly visible to the eye or lens. In the quartzites the fractured surface is uneven, splintery, or conchoidal; the luster is vitreous like that of quartz, and the grains are imperceptible or nearly so. This difference arises chiefly from the fact that when the sandstone is broken the fracture takes place in the cement, leaving the grains unbroken and outstanding, while in quartzite the grains are so firmly cemented that the rock is nearly of uniform strength throughout and the fracture takes place through cement and grains alike. This difference will serve as a practical distinction between the two rocks.

Minerals and General Properties. While some quartzites are very pure in mineral composition, others carry in greater or less abundance other minerals, which may be in part remains of original mineral grains, such as feldspar, mixed with those of quartz, or new ones which have resulted from the metamorphism of the clay or calcareous cement that formerly filled the interstices between the grains of the sandstone. Such are muscovite, chlorite, cyanite, epidote, etc. Iron hydroxides may be converted into magnetite or hematite, and carbonaceous substance into graphite. These resultant minerals are usually of microscopic size, and may give the rock a distinct color — green, blue, purple, black, etc.; sometimes they are large enough to be clearly seen with the lens. The most important of them is muscovite, which, as it increases in amount, gives the rock a more schistose character, through which it attains a capacity for cleavage along the planes of the mica. Eventually this abundance produces a transition into mica schist, as previously explained under that rock. The normal *color* of quartzite is white, light-gray or yellowish to brown, but these colors are often modified by included material acting as a pigment, as explained above. The *jointing* of quartzite is usually platy, but sometimes very massive, and such rocks are in some places quarried and furnish good material for structural purposes.

The chemical composition of a pure quartzite is nearly that of silica alone, but as more or less clay or calcareous material was mixed with the sand, small amounts of alumina, iron, lime, and alkalies appear. This is illustrated in the contrast between the two analyses quoted below.

	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	H_2O	Total
I...	97.71	1.39	1.25	...	0.13	0.18	...	...	...	100.66
II..	74.22	10.61	7.45	0.85	1.48	0.56	2.12	1.08	1.79	100.16

I, Pure quartzite, Chickies Station, Pa.; II, Impure quartzite, Pigeon Point, Minn. Contains small quantities of feldspar, mica, chlorite, and magnetite.

Varieties. The different varieties of quartzite are chiefly those occasioned by the presence of some included substance. Thus we have epidotic quartzite, graphitic quartzite, sillimanite quartzite, and many others. Micaceous quartzite is also called quartz schist. In very strongly folded and compressed mountain regions even pure quartzite may suffer such shearing as to break and crush the original grains and impose a more or less schistose structure. Such rocks are called *stretched* quartzites. In some places these rocks contain pebbles, of varying sizes, which retain their original shape and are sometimes by pressure and shearing reduced to lenticular, ovoid, or cylindrical bodies. These are called *conglomerate-quartzite* and were formed from gravels, like conglomerate gneisses and conglomerate-mica schists.

Oölitic quartzite is a variety consisting of rounded grains, composed of chalcedony, a slightly hydrated form of silica, deposited around fragments of quartz which serve as nuclei. It resembles the roe of a fish, and if the globules are sufficiently large, their concentric structure can be plainly seen with a lens on the broken or polished surface of the rock. Such quartzites have been found at State College, Pa., and in Sumatra. *Buhrstone* is a name given to a variety of quartzite which is full of long, drawn-out hollows or pores. Notwithstanding the porosity, it is quite firm and its hardness and toughness have caused its use as a millstone. It is thought to have been originally more or less of a limestone, filled with fossils, which, by the action of solutions containing silica, has been converted into a quartzite, consisting mostly of chalcedony, the cavities of which represent the leached-out fossils. It occurs in western Massachusetts, Georgia, South Carolina, and in the Paris Basin in France. It is chiefly of Tertiary age.

Occurrences. Quartzite is a widely distributed rock, mostly among the older metamorphosed strata. Thus it is common in eastern North America, in the Rocky Mountain Cordillera, and in various localities in Europe and other parts of the world. The occurrence of some special varieties has already been mentioned.

Alteration. On account of the insoluble, unyielding nature of its constituent grains and their cement, quartzite resists erosion and the atmospheric agencies well, and, where it is prominent in mountain regions and areas undergoing denudation, it forms prominent features of the landscape, bold ledges, cliffs, castellated crags, spires, etc. Eventually the rock breaks down into sandy soil of poor quality.

Distinction from Other Rocks. Quartzites, which are very homogeneous-appearing rocks, may be confused in the outcrop or hand specimen with some limestones or felsites of a similar color and texture. From the limestones they are easily distinguished by a test of the hardness, or by lack of effervescence with acid; from the felsites, in the field by the different mode of geological occurrence, by the cleavage of the feldspar if visible under the lens, or by blowpipe test. It should be remembered that the chief minerals composing these three rocks are quartz, calcite, and feldspar respectively, and they should be tested accordingly.

Slate

Slates are homogeneous rocks, of such fine texture that the individual mineral particles composing them cannot be distinguished by the eye or lens, and characterized by a remarkable cleavage, by means of which they split readily into broad, thin sheets, which, as is well known, may be used for a variety of purposes.

The slates represent, in mildly metamorphosed condition, the finest material of the land waste caused by erosion, the same material that, among the unmetamorphosed stratified rocks, appears as clay, shales of various kinds, etc., as previously described. With such material more or less volcanic dust and débris, or tuffs, may be mingled. The cause of the slaty cleavage is discussed in one of the paragraphs that follow. The difference between slate and shale has been discussed in the description of the latter rock.

Mineral Composition and Other Properties. The mineral particles are so fine in slate that the composition from the megascopic standpoint is not a matter of importance. It may be mentioned, however, that since the clays, silts, etc., from which they are formed come from a great variety of sources, the microscope detects in them many and varied minerals, the chief of which are quartz, mica, chlorite, carbonaceous substance, etc. The kaolin and feldspar particles, which one might naturally expect, are rare and appear to have been converted into other minerals. Slates not infrequently contain crystals of pyrite, which may be readily seen with the eye or lens, and which may attain large size, sometimes as distinct crystals, sometimes as concretions or replacing fossils. Veins, lumps, and lenses of secondary quartz are also common in them, those of calcite more rare. The *color* is chiefly gray, to dark gray, to black, according to the amount of carbonaceous substance, but they are often green from chlorite, or red, purple, yellow, or brown, from the oxides of iron. The surface of the slaty cleavage tends to have more or less of a silky luster, sometimes scarcely perceptible; the cross fracture has a dull surface. While the rock is firm and never friable, it is also rather soft, so that it may be quite readily cut, a feature of great value for technical purposes. The specific gravity of an average slate is about 2.8. The chemical composition is shown in the following analyses of typical examples, made in the laboratory of the U. S. Geological Survey.

	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	H_2O	C	XyO	Total
I	59.7	17.0	0.5	4.9	3.2	1.3	1.4	3.8	4.1	0.5	3.8	100.2
II	67.6	13.2	5.4	1.2	3.2	0.1	0.7	4.5	3.3	...	0.7	99.9
III	59.8	15.0	1.2	4.7	3.4	2.2	1.1	4.5	3.8	...	4.3	100.0
IV	56.4	15.3	1.7	3.2	2.8	4.2	1.3	3.5	4.8	0.6	6.5	100.3
V	60.5	19.7	...	7.8	2.2	1.1	2.2	3.2	3.3	...	...	100.0

I, Black roofing slate, Benson, Vermont. XyO = TiO_2, P_2O_5, CO_2, FeS_2, etc.; II, Red roofing slate, Washington Co., New York State; III, Green roofing slate, Pawlet, Vermont, CO_2, 3.0; IV, Black roofing slate, Slatington, Pennsylvania, CO_2, 3.7; FeS_2, 1.7; V, Roofing slate, Wales.

The general predominance of magnesia over lime in the analyses, as well as the small amount of the latter, shows that the soluble calcic silicates have been mostly dissolved out of the silt in the process of erosion and laying down of the sediments. The presence of carbon in the black varieties, and of ferric iron in the red, is to be noted.

Varieties. Roofing slates are compact, very fissile varieties which split with a smooth, even cleavage. All the different colors are used, but the most common is a dark gray. Some slates fade when taken from the quarry, on continued exposure, through incipient alteration; and the possibility of this can only be determined by practical trial. The presence of pyrite in any notable quantity is very prejudicial, as this substance on exposure quickly alters and gives rise to rusty stains. The slates used for blackboards and ciphering are the blackest and most compact kinds. *Calcareous* slates are those that contain a good deal of intermingled calcite, or chalky material, which may rise to 30 per cent of the whole; they represent slates that have been formed from original marls.

Cleavage of Slates and Its Origin. The cause of slaty cleavage has occasioned much speculation and has been the subject of investigation, both experimental and mathematical, as well as geological, by a number of scientists. From this work it has become clear that slaty cleavage is the result of great pressure upon the material and that the planes of cleavage are at right angles to the direction of pressure. When the fine-grained sediments are subjected to intense pressure, unevenly shaped particles tend to rotate, so that their longer axes are perpendicular to the direction of pressure; they also tend to become flattened perpendicularly to it. This tends to give the rock a grain, an arrangement of particles, by which it splits more readily along such a direction than in any other. Moreover the rock minerals, which naturally tend to be flattened or elongate in the shape of their particles, such as the micas, kaolin, hornblende, chlorite, etc., possess an excellent cleavage parallel to the elongate or flattened directions, and this is a great help in promoting the capacity of the rock cleavage. Slaty cleavage is thus partly molecular, or mineral cleavage, where it passes through a single mineral particle, and partly mechanical where it passes between arranged, unlike mineral particles. Not all of the minerals whose cleavage and arrangement induce the slaty cleavage are necessarily original; some of them, micas for example, may have been formed by the metamorphism accompanying the pressure.

The planes of cleavage do not necessarily bear any definite relation to those of original bedding. The beds were laid down horizontally and the direction of pressure is also usually horizontal; the cleavage planes are at right angles to this, and may therefore cut the bedding at right, or highly inclined, angles. But, as the beds may be folded before the pressures become intense, the cleavage planes may pass through the bedding at various angles, although they themselves are strictly parallel, as seen in the diagram, Fig. 74.

Fig. 74. Slaty Cleavage in Folded Beds

Slates, in addition to their cleavage, are intersected by cross joints which are frequently so numerous as to divide them into small blocks and prevent their technical use. They generally form systems intersecting at definite angles. In the older mountain ranges the slates have generally been crumpled by later foldings and show on their cleavage surfaces the effects of these deformations.

Occurrence. Slates are common rocks in metamorphic regions and range geologically from the Algonkian up to recent periods. In eastern North America they are chiefly Paleozoic and have an extensive development in Maine, in Vermont, in Pennsylvania, and in Georgia. They are also extensively distributed in the Lake Superior region and in the older ranges of the Rocky Mountain Cordillera. They are found in southern England, in Wales, and in many other parts of Europe.

Phyllite. Closely connected with slate by intermediate varieties is a group of rocks to which the name of phyllite has been given. The name means "leaf stone" and was given to them on account of their well-defined cleavage, though this cleavage is not peculiar to them and is equally well developed in slates and mica schists. The surface is sometimes flat, sometimes curved, folded, or crumpled by crustal movements. Phyllite differs from ordinary slate in containing a larger amount of mica, or at all events the mica is in larger flakes and is more evident, giving the surface of cleavage a shimmering or micaceous appearance, and thus furnishing a transition form between slate and mica schist. The mica is a fine, scaly, silky variety of muscovite to which the name of *sericite* has been given. Quartz is the other chief mineral and may sometimes be seen on the cross fracture. The rocks that in this country have been called "hydromica-schists" are in large part such phyllites. Their color is sometimes pure white, more often tinged with reddish, yellowish, or greenish tones, and sometimes dark colored, or black, from pigments like those of slate. They are likely to have a soft talcy or greasy feel, to be more brittle than slate, and to lack its toughness and firmness. Sometimes they contain visible crystals of pyrite, garnet, and other minerals.

The origin of phyllites, as shown by the researches which have been made upon them, is a varied one; some phyllites represent sedimentary material which has been metamorphosed, like the slates, but has attained a more advanced degree of recrystallization than they have. On the other hand, a considerable part of the phyllites represent original felsites or felsite tuffs which have been subjected to the energetic operation of metamorphism through dynamic forces, to pressure and great shearing, aided probably by liquids and heat. Their feldspars have been largely, if not entirely, converted into mica, and a thin schistose or slaty cleavage has been imposed upon them. In some extreme cases the rock appears as if wholly composed of this silky mica. The chemical analyses of these rocks show them to have a composition similar to that of many felsites or felsite tuffs.

Porphyroid — Sheared Felsites. In many places where phyllites occur, they may be traced into types which are firmer, with less pronounced but yet distinct cleavage, and which contain visible phenocrysts of quartz and feldspar, similar to those in felsite porphyries (embedded in the phyllitic ground mass). Such rocks have been termed *porphyroid.* These again may be further traced into undoubted felsites which still retain the phenocrysts, flow structures, spherulites, etc., characteristic of lavas, or the broken, angular, fragmental features of tuffs and breccias, in spite of the slaty cleavage that to a greater or lesser degree has been imposed upon them by the dynamic movements and shearing to which they have been subjected. These again may be followed into undoubted, unsheared felsites. Rocks with these characters, in their varied types as described above, occur in various places among the older metamorphosed areas of eastern North America, in Maine, at South Mountain, Pennsylvania, in Virginia and North Carolina, in Wisconsin, the Lake Superior region, etc. They have been found of various ages in Great Britain, Germany, the Alps and other places in Europe. In Sweden such ancient felsites and felsite tuffs, hardened and more or less metamorphosed, have been termed *hälleflinta.*

It is only in comparatively recent years that such altered igneous rocks, with more or less schistose appearance and cleavage, have been recognized and their significance appreciated. The older geologists, confused by the cleavage, regarded and mapped them as slates and considered them as of sedimentary origin. They are of interest, because, as stated in the introduction to metamorphic rocks, these latter comprise material both of igneous and sedimentary origin. Of the feldspathic, igneous rocks, the coarser-grained ones, like granite, as we have seen, yield gneisses; the compact felsites and their tuffs under the metamorphic agencies of pressure, shearing, etc., are turned into phyllites, porphyroids, and compact slaty rocks, according to the degree to which these agencies have acted. The igneous ferromagnesian rocks we shall see later among the amphibolites and other schists.

Talc Schist

Talc schist is a rock of pronounced schistose cleavage and character, in which talc is the predominant mineral. The talc is present in fine scales to coarse foliated aggregates. Other minerals also occur in different varieties of the rock, such as quartz in grains, lenses, and veins; or magnetite and chromite in black specks and grains; hornblende, usually in white or green prisms, or crystals of enstatite; chlorite mingled with the talc, etc. The color is usually light, white to pale green, or yellowish, or gray; sometimes dark gray or greenish. The rock is soft and the talc gives it a greasy feeling, and often a pearly or tallowy appearance on the cleavage surface. In addition to its micaceous appearance and soft greasy feel, the talc is easily recognized by its infusibility before the blowpipe, and its insolubility in acids. The rock cleavage is sometimes thinly fissile, sometimes thicker; and sometimes cleavage is nearly wanting, the rock is more nearly massive, is compact, and has a lard-like or wax-like aspect, and approaches soapstone in character. Chemically, these rocks consist mostly of silica and magnesia with small amounts of water and other oxides.

	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O+K_2O	H_2O	Total
I...	58.7	9.3	4.4	...	22.8	0.9	... ...	4.1	100.2
II..	53.3	4.4	5.8	1.0	29.9	1.5	1.5	2.6	100.0

I, Talc schist, Falun, Sweden; II, Talc schist, Zöbtau, Moravia, Austria.

The composition is quite similar in its general features to that of the peridotites among igneous rocks, as may be seen by reference to their analyses.

The talc schists undoubtedly represent material that was sometimes of igneous origin, — peridotite, pyroxenite, or dunite — and sometimes of sedimentary origin — dolomitic, ferruginous marls, etc. It may not be possible from field work and an inspection of specimens alone, unless aided by chemical analyses and microscopical study, to decide in any given case which origin the material had, and sometimes not even then. The presence of chromium, either in the form of chromite or of secondary minerals derived from it, such as kämmererite or fuchsite (a variety of muscovite green from chromium), is indicative of igneous origin, while that of much quartz and dolomite mingled with the talc, which produces the variety of talc schist called *listwänite*, would be, on the other hand, more indicative of a sedimentary one.

Talc schists do not make important formations like gneiss, mica schist, and slates, but are limited in occurrence, being found as interbedded layers or inclusions, chiefly lenticular masses, in other metamorphic rocks, and are really not very common. They show transitions in places into other rocks, such as chlorite schist, dolomite marble, quartzite, etc. Such transitions, or the lack of them, may furnish useful hints in regard to the origin of the talc schist in particular cases. In eastern North America talc schists occur, associated with other metamorphic rocks, in Canada, in the New England States, in northern New York, and south to Georgia. They are also found in the Rocky Mountain region and in the Pacific States, California, Oregon, etc. In Europe they occur in the Alps, Germany, and various other places, in Sweden, Finland, etc. They also occur in Brazil and other parts of the world. Their occurrence, though not generally of wide geologic interest, is important because they furnish a source of supply for talc, which is used for a variety of purposes.

Chlorite Schist

These rocks are schists that have chlorite as their chief distinctive mineral. The chlorite occurs as fine, scaly aggregates, sometimes too fine for the individual scales to be seen by the eye; more rarely in foliated to coarse foliated aggregates. It is sometimes thinly, sometimes thickly, schistose, and sometimes almost massive; and although the rock is very soft and may be readily cut, it is very tough in the more massive varieties. The color varies through different shades of green.

yellow-green, to dark green. Different minerals are likely to accompany the chlorite, chief among which are quartz and sericite; others that may be mentioned are magnetite, often in fine crystals; hornblende in slender needles or prisms; corundum and cyanite occasionally; epidote in grains and crystals; in some instances albite, graphite, calcite, dolomite, etc. The chemical composition of these rocks is very variable: it indicates that they have resulted from several different sources, as seen in the following analyses.

SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	H_2O	XyO	Total
49.2	15.1	12.9	...	5.2	10.6	3.6	1.5	1.9	...	100.0
26.2	23.7	15.7	14.5	8.3	1.7	0.5	0.6	7.3	0.8	99.3

I, Chlorite schist, east of Rotön, Sweden; II, Chlorite schist, Benguet, Luzon Island, Philippines.

As may be seen by reference to their analyses, No. I has a composition very similar to that of the group of igneous rocks known as gabbros, to which the dolerites and basalts also belong, these being merely texturally different products of magmas similar to those of gabbros. No. II, on the other hand, is very different, and does not correspond to any igneous rock; it suggests rather a very ferruginous clay.

The chlorite schists are of wide distribution, forming subordinate layers or masses in the midst of gneisses, mica schists, and other such rocks, characteristic of metamorphic areas. Thus they occur in Canada, New England, New York, Pennsylvania, etc. They are also common in Europe, in the Alps, Germany, Sweden, and other places.

Greenstone. Transitions of chlorite schist into mica schist, into slates, into schistose serpentine, and into hornblende schist occur in places. Under the description of gabbro and of dolerite it was mentioned that these rocks by alteration, through processes of regional metamorphism, passed into hornblende schists and into so-called " greenstone " or " greenstone schist." Here the original ferromagnesian minerals, or the hornblende produced from them, have been largely changed by alteration into chlorite, which gives the rock its green color. Such greenstones (if massive), or greenstone schists (if schistose), which thus represent altered dolerites, basalts, and gabbros, form transition types to chlorite schist. The alteration of hornblende in diorites to chlorite also produces greenstones. It is conceivable that a dolerite might pass directly by alteration into a chlorite rock, or greenstone, and thus be of massive character, or it might be first changed into a hornblende schist and this might secondarily alter into a chlorite schist. But since hornblende schists are produced, not only from igneous but also from sedimentary beds, as described in the account of these rocks, the mere fact that transitions from hornblende schists into chlorite schists occur does not alone prove that these latter have been derived from igneous rocks in any given case. Transitions from dolerite into chlorite rocks, or greenstone schists, have been observed in many regions: in Michigan, Maryland, Connecticut, in the south of England, in the Alps, Germany, etc. A greenstone schist from the Menominee River, Michigan, which is known to be an altered dolerite, has the following composition.

SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	H_2O	CO_2	Total
44.5	16.4	5.1	5.5	7.5	7.9	2.6	0.5	5.0	5.4	100.4

It is composed of chlorite, with some feldspar, quartz, and calcite. This should be compared with the analyses of gabbro which represent the gabbro-dolerite group.

The greenstones vary in color from pale gray-green through yellowish green to dark green. The color depends on the proportion of chlorite to other minerals. They are generally too compact for the megascopic determination of the individual mineral particles. They are as a rule rather soft rocks. Sometimes, when the original dolerite or basalt was an amygdaloid, this amygdaloidal structure is retained and the rock is filled with little balls of calcite or quartz. Where the rock has been strongly sheared, these have disappeared, but are still represented in the schist by ovoid spots of a different color and mineral composition from the main mass. In some rare instances they have been replaced by ores. The amygdaloidal structure is a good proof of the original igneous character of the rock.

Soapstone, Steatite. As an appendix to talc and chlorite schists may be mentioned soapstone, or steatite, a massive rock, usually of a gray or green, but sometimes of a dark color; the lighter colored rock often with a silvery or shimmering fracture surface. It is very soft, easily cut or worked, without cleavage or grain, and resists heat and the action of acids well. For these reasons it was extensively used in prehistoric times for the manufacture of pots and other vessels, and is employed at present in table tops, sinks, and other interior fittings where its qualities render it valuable. It is usually a variable mixture of interwoven scales of talc and chlorite with various minerals; sometimes carbonates are present. The better qualities incline more nearly to pure talc. The minerals are in general too fine for megascopic determination. It occurs in connection with talc and chlorite rocks, and sometimes with serpentine, in various parts of the world, in areas of metamorphic rocks.

Amphibolite and Hornblende Schist

The amphibolites are a large group of metamorphic rocks, the distinguishing characters of which are that they consist partly or largely of amphibole and that they possess a more or less pronounced schistose structure. There are a number of varieties in the group, depending on the kind of amphibole present, and on the minerals associated with it, so that it is difficult to give a general description which will cover all cases. It is best therefore to describe the most common kind first, and then give a brief mention of some of the less common varieties.

Amphibolites are rocks which vary in color from green to black; the green is of varying tones, clear light green, gray-green, yellowish green to dark green, greenish black to black; the darker colors are more common. The color is given by the particular amphibole present though it is sometimes influenced to a considerable degree by admixed chlorite. The grain of the rocks varies from coarse to fine, the latter being more common. When coarse, the amphibole, which is almost always present in slender prisms or blades and rarely in grains, is easily recognized by the eye from its form and bright, good cleavage. The prisms may be an inch or more in length and have the thickness of a slender match stick; from this, in the finer-grained types, they sink to tiny needle- or hair-like prisms which can only be seen by careful observation with a good lens. The prisms are usually arranged in the direction of schistosity and thus approach parallel positions; it is this which chiefly gives the rock its cleavage. It also gives the rock, especially in the finer-grained types with needle-like prisms, a shimmering or silky luster on cleavage surfaces, which is rather characteristic. The grain of some varieties is so extremely fine that not even with the lens can the individual minerals be seen; such rocks may appear very much like slates, and are indeed difficult to distinguish from them; they are, however, not very common types.

The amphibolites are rather hard rocks, not easily scratched by the knife. In the more schistose types they are brittle, but as they become more massive in character they are very tough and difficult to break. They are heavy, the specific gravity ranging from 3.0 to 3.4.

In addition to the hornblende other minerals are present in varying kinds and quantities; prominent ones are quartz, feldspar, and mica. The quartz and feldspar in grains are best observed with the lens on the cross fracture; often they are too fine and too much masked by the hornblende to be seen; the quartz also at times forms little lenses or masses, or fills fractures in the shape of veins, as in other metamorphic rocks, and has then been secondarily deposited from solutions. The mica can generally be seen on the surface of chief fracture; both biotite and muscovite occur and may increase to such an extent as to produce formal transitions to mica schist.

Other minerals which may be detected megascopically are iron ore, pyrite, garnet in small dark red crystals, chlorite, calcite; the calcite sometimes occurs in veins, etc., like quartz. Pyroxene, epidote, and other minerals occur, but partly on account of the fineness of grain, and partly on account of their resemblance to hornblende, it is usually impossible to detect and identify them without microscopic study.

The chemical composition of amphibolites shows, in agreement with facts to be presently mentioned, that the origin of these rocks is various. The following analyses will do for examples.

	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	H_2O	XyO	Total
I	49.9	15.5	3.0	8.0	7.8	8.9	3.3	0.7	1.5	1.7	100.3
II	50.4	13.3	6.3	9.3	5.6	7.9	2.1	1.1	1.7	2.0	99.7
III	55.0	2.9	0.8	6.3	21.0	11.5	0.3	0.2	1.0	1.5	100.5
IV	55.6	16.3	1.2	7.2	5.6	9.2	0.9	0.2	3.1	1.0	100.3
V	52.4	13.6	2.7	9.8	5.5	10.0	2.3	0.4	1.7	1.6	100.0

I, Thin schistose amphibolite, Whitman's Ferry, Sunderland, Mass.; II, Amphibolite, Crystal Falls district, Michigan; III, Grass-green amphibolite, Chiavenna. $XyO = Cr_2O_3$; IV, Amphibolite, Goshen, Massachusetts; V, Olivine basalt, main lava flow, Pine Hill, South Britain, Connecticut.

Of these analyses Nos. I and II have compositions very much like that of the gabbro-basalt magmas, as may be seen by comparison with No. V; No. III has the general composition of the peridotite-pyroxenite group of igneous rocks and may be compared with Analysis No. III of that group. The presence of Cr_2O_3 in III is also significant of an igneous origin. On the other hand No. IV is thought on geological grounds to be derived from an impure limestone, probably full of clay, and this supposition is rendered probable by the fact that the high alumina is accompanied by an almost entire lack of alkalies, a feature not seen in igneous rocks.

Origin of Amphibolites. As just shown, the composition of amphibolites sometimes corresponds with that of igneous rocks, and sometimes does not, and this agrees with the results of geological investigation in the field. For in some places we find them under conditions which strongly suggest their derivation from igneous rocks, and in other places such evidence is either wanting, or the contrary is indicated. The use of the microscope on thin sections, by which the textures and associated minerals may be seen, also leads to the same conclusions.

In the description of gabbro and dolerite it was mentioned, under alteration, that these rocks by pressure and shearing become converted into hornblende schist or amphibolite. Gradual transitions from one kind into the other, without geological break, are found. Thus as the feldspathic igneous rocks give rise to gneisses, phyllites, etc., so the ferromagnesian, especially the pyroxenic, igneous rocks give rise mainly to hornblende schists, and also to talc schists, chlorite schists, and serpentine.

Sedimentary beds of impure mixed character, such as limestones containing sand, clay, and more or less of the hydroxides of iron, limonite, etc., or marls of a somewhat similar nature, if subjected to metamorphism, might, under suitable conditions, be converted largely into hornblende, mixed with other minerals. The volatile constituents — the water, carbon dioxide, etc., — are then mostly driven out; the bases — lime, iron, magnesia, and alumina — combine with the acid silica to form silicates, of which hornblende is the chief and determinant one of the resulting rock. Thus hornblende schists result from the metamorphism of sedimentary strata, and may be one form of the alteration of limestone, as described later under marble.

Varieties of Amphibolite. In the midst of gneisses and mica schists amphibolite sometimes assumes a very massive character. The prisms and grains of hornblende, instead of being arranged in parallel position, and thus producing a schistose cleavage, are interwoven without arrangement, and cleavage is wanting. Especially in such massive types is the hornblende likely to be accompanied by feldspar. If the feldspar should increase and dominate, transitions to hornblende gneiss would be produced. There is a tendency on the part of some to restrict the term amphibolite to such massive varieties and to use amphibolite schist for those with distinct schistosity but this distinction has not yet come into general use.

Glaucophane schist is a variety of amphibole schist in which the distinctive amphibole is the blue soda-bearing species, glaucophane, and for this reason the rock is colored blue instead of green. Various other minerals may be present, depending on the origin, such as quartz, epidote, pyroxene, chlorite, garnet, etc. Some glaucophane schists are coarse-grained and these other minerals may be seen in them; some are fine-grained and appear as slaty blue or blue-gray rocks. Studies which have been made of them show that sometimes they have been produced by the metamorphism of sedimentary, sometimes of igneous, material. While comparatively rare, they have been found widely distributed in California, Brittany, the Alps, Island of Syra, Greece, Japan, Australia, etc.

Greenstone schist in its relation to amphibolites has already been mentioned under chlorite schist. As the use of the term " greenstone " has been vague, applying rather to color than to a determined mineral composition, many rocks that are hornblende schists, rather than chlorite schists, have been included under it.

Occurrence of Amphibolites. These form layers and masses in other metamorphic rocks, especially in gneisses and mica schists, and also occur as extensive independent formations. They often occur in gneisses in long bands or veins in such a manner as to suggest that they are metamorphosed dikes of doleritic rock. In size the masses may vary within the widest bounds, from one foot to thousands of feet in diameter. In some places, they make up in frequency of occurrence what they lack in size. The manner in which they are interlaminated in places with other metamorphic rocks suggests that they may have been formed sometimes from intrusive sheets of igneous rock, and sometimes from interbedded sediments; but in general this can only be rendered certain by further chemical and microscopical investigation. Their occurrence as mantles around igneous masses has already been mentioned.

The amphibolites are extremely common rocks in all metamorphic regions. Thus they are found commonly distributed in New England and New York State, and southward to Georgia; in Canada, the Lake Superior region, the Sierras, in England, Scotland, the Alps, etc.

Alteration. It has already been pointed out under chlorite schists that the hornblende of these rocks may be changed into chlorite. In another form of alteration it may be turned into serpentine with other minerals, and thus give rise to serpentine rocks, the character of which is described later. These changes take place in the upper belt of metamorphism, that of hydration and cementation, and are secondary to the processes that have produced the amphibolite from something else. They might thus be spoken of as tertiary changes.

By the ordinary process of weathering on the surface, these rocks change to masses of limonite, clay, calcite, etc., which form ferruginous soils.

Marble and Carbonate-silicate Rocks

Marble is the metamorphic condition of sedimentary rocks composed of calcium carbonate, $CaCO_3$, which in their ordinary stratified form are known as limestone, chalk, etc. It is distinguished from these rocks by its crystallization, coarser grain, compactness, and purer colors. But just as we have ordinary limestones which contain only calcium carbonate, and dolomitic limestones which contain dolomite in variable quantity associated with the calcium carbonate, so we have calcite marbles and dolomite marbles. As this distinction is a purely chemical one which is rarely made, and indeed rarely can be made in ordinary and commercial usage, the rock is, therefore, called marble, without regard to whether it contains magnesia or not. But geologically, especially from the petrographical standpoint, there is an important difference between the two rocks in respect to the associated minerals they are likely to contain when impurities were present in them originally, and therefore they are treated separately in this work for reasons which will presently appear.

General Properties. Marble is a crystalline granular rock composed of grains of calcite; sometimes these are cemented by a fine deposit of calcite between them. The grain varies from very coarse to such fine compact material that individual grains cannot be distinguished; in the coarsest varieties, the cleavage surfaces of individuals may attain a breadth of half an inch or more, but this is unusual. The fracture surface of the finest-grained kinds has a soft shimmering luster, while the appearance of coarser kinds is like that of loaf sugar. The normal color is white, like that of the best statuary marble, but the rock is usually more or less colored by various substances which act as a pigment, the principal ones being carbonaceous matter and the oxides of iron. It thus becomes gray, yellow, red or black, and while the color is sometimes uniform, it is more generally spotted, blotched, clouded or veined, producing that effect which is known as "marbled." The hardness is that of calcite, 3; the rock is thus readily scratched or cut by the knife, a ready means of distinction from quartzite or sandstone, which may resemble it. It is readily soluble in weak acids. Unless the grain is too fine, the good rhombohedral cleavage of the calcite grains can be easily seen with a lens. The chemical composition of a perfectly pure marble would be that of calcite, $CaO = 56$, $CO_2 = 44$ per cent, but there are usually small quantities of magnesia, alumina, iron, and silica present, coming from traces of sand, clay, dolomite, etc., mixed with it; these may increase until the impure marbles, which are described in a later paragraph, are produced.

Unlike most metamorphic rocks, marble, if pure, is very massive and shows no sign of schistose cleavage, even where its association with schists is such as to indicate that it must have been subjected to enormous pressure and shearing stresses. If impurities in the form of other minerals are present it may then assume cleavage, caused by their presence. The reason for this want of cleavage has caused much speculation; it is probably due to several causes, to the purity of the rock, to a rolling of the grains among themselves, but chiefly to a curious property which calcite possesses of permitting movement among its molecules, whereby new crystal forms are produced without destruction of its substance; this results in a complicated microscopic twinning, somewhat similar to that explained under feldspar. As a result of this the stresses are absorbed molecularly, instead of producing changes in the outward structure, as in most rocks.

Varieties of Marble. The varieties of marble from the technical point of view are chiefly those based on color. *Statuary marble* is the purest and whitest kind. *Architectural marbles* are those of the most uniform tones of color, while *ornamental marbles* are those distinguished by striking effects of varied colors, as mentioned above. In the trade, the term marble is used for any calcium carbonate or dolomite rock that can be procured in large, firm blocks and is susceptible of a high polish; under this definition many limestones are included. *Shell marble* is thus a hard, firm limestone in which a pattern is given by the presence of certain fossils, shells of brachiopods and remains of crinoid stems being the most common. The different yellow, red, and black marbles, most of them veined and clouded, of Italy, Greece, and the East, have long been distinguished by a host of names.

Those varieties that depend on the presence of some mineral, in addition to the calcite, are treated in the following section on carbonate-silicate rocks.

Occurrence of Marble. The great deposits of marble, from which the material used for structural purposes is taken, are the result of regional metamorphism and occur therefore in regions of metamorphic rocks associated with gneisses, schists, etc., in the form of interbedded masses, layers, or lenses. These vary in size within wide bounds, from a few feet to many miles in length. Marble forms immense interbedded layers, or masses, in the Pre-Cambrian (Grenville) rocks of Canada; it occurs in quantities in Vermont, Massachusetts, Georgia, and Tennessee, in which States it is extensively exploited, in Colorado, and in other places in the West. The marbles of Greece and Italy have attained celebrity from their use by the ancient Greeks and Romans in statuary and buildings. Marble is found in the Alps, Germany, and Scandinavia, and in various other places in the world.

Marble is also produced from limestone (and chalk) by the contact action of intruded igneous rock. Although some very coarse-grained material may be formed in this way, the amount of commercially valuable marble is usually small.

Calcium Carbonate-Silicate Rocks. As stated under the general properties of sedimentary rocks, all transitions occur between limestones and sandstones, between limestones and shales, and among the three combined. This means, merely, that the original calcareous deposits may have had sand, clays, silt, and ferruginous material in variable amounts mixed with them. Chemically, it means that the calcium carbonate has silica, the oxides of aluminum and iron, and usually small amounts of other things, such as magnesia, potassa, and soda, mixed with it. Under the conditions of metamorphism the carbon dioxide, CO_2, is driven out, to be replaced by an equivalent amount of silica, SiO_2, and thus silicates of calcium, of calcium and aluminum, of calcium and iron, or mixtures of these, or combinations containing other elements as well, are formed. Also volatile substances, liquids and gases, such as water vapor furnishing hydroxyl, fluorine, boron, etc., emanations from magmas resting below or being intruded simultaneously with the crustal movements which give rise to the metamorphosing conditions, may enter the rock mass and thus, in adding new substances, produce additional mineral combinations. The amount of silica present may be sufficient to replace the carbon dioxide completely, producing a rock composed entirely of silicates; or it may not be sufficient to accomplish this. In the latter case the mass consists of a mixture of calcite and silicates. Thus all transitions may be found from pure marble, through varieties containing bunches, masses, and individual crystals of some mineral, or minerals, into rocks completely made up of silicates, sometimes of one silicate, but usually of a mixture of them. The whole affair is quite analogous to what has already been described in a previous part of this book as the effect of contact metamorphism of igneous rocks on impure limestones, and the chemical reactions which take place are the same as those there mentioned. The resulting rocks are also quite similar, with, however, one difference. In contact metamorphism the chief agency is heat, while pressure and shearing are either wanting, or are relatively of slight importance; but in regional metamorphism pressure and shearing are factors of great intensity. Thus the rocks of contact metamorphism are massive and with little or no foliation, while those produced by regional metamorphism may have well-developed foliation.

Important minerals that thus occur in limestone are *pyroxenes* (especially wollastonite, $CaSiO_3$, and diopside, $CaMgSi_2O_6$); *garnets* (especially grossularite, $Ca_3Al_2(SiO_4)_3$); amphiboles (especially tremolite, $CaMg_3Si_4O_{12}$); *feldspar* (especially anorthite, $CaAl_2Si_2O_8$); *vesuvianite; epidote; fluorite,* etc. A whole host of other minerals occur, but many of them, such as graphite, magnetite, spinel, titanite, tourmaline, apatite, phlogopite, etc., come chiefly from the impurities in the original rock, which have been caused to combine to form new minerals.

It is clear from this, that, depending on the original chemical composition, a great variety of these calcium carbonate-silicate rocks exist, but only a few of the most important types can be mentioned.

Wollastonite rock. Marble not infrequently contains crystals of the pyroxene-like mineral, wollastonite, $CaSiO_3$, and this may increase until the rock is practically composed of it. It is commonly accompanied by diopside, hornblende, etc. The rock is white, generally massive, and resembles marble, from which it is easily distinguished by its superior hardness. It occurs in California, the Black Forest, Brittany, etc.

Garnet rock, or Garnetite. This is an aggregate of grains of garnet, generally accompanied by various other minerals in smaller, variable amounts. If some calcite is present the garnets may show more or less crystal form; sometimes the calcite has been leached out and the rock is porous. Garnet rock tends to be yellowish, to reddish brown, in color. Considerable magnetite is often present. This rock occurs in New England, northern New York, Montana, Germany, the Alps, etc.

Epidote rock, or Epidosite. This is composed chiefly of epidote with other minerals, quartz, garnet, etc. Sometimes massive granular, sometimes schistose. Greenish in color, especially of a yellow-green. Often very tough under the hammer. New England, Brazil, Germany, etc. Sometimes the ferromagnesian igneous rocks, basalt and dolerite, under proper metamorphic conditions, are converted into a rock consisting chiefly of epidote, instead of hornblende or chlorite as previously described, and of a yellowish green color. They may resemble the above, but can usually be distinguished by their mode of occurrence, geologic relations, greater uniformity, and often by the remains of special structures, such as the amygdaloidal. Instances occur in Pennsylvania, Virginia, etc.

Pyroxene rock. This rock consists chiefly of pyroxene, of which the variety diopside is prominent. Other minerals, quartz or calcite, etc., may occur. White, greenish, to dark green in color, massive or schistose. Is found in Massachusetts, northern New York, Germany, Bohemia, Sweden, etc. Under the head of metamorphic pyroxene rocks there may be mentioned in this connection jade, which, although extremely rare, is of great interest from its ethnological and artistic importance. *Jade* is a fine-grained, and usually compact, aggregate of grains and fibers, of the soda pyroxene, jadeite, $NaAlSi_2O_6$. It is sometimes snow-white, resembling marble, but usually greenish (or with a violet shade) to dark green. The greenish colors are also clouded, veined, or specked through the white. When polished it has a soft, somewhat greasy luster. The extraordinary toughness of the rock is one of its most marked characters and on this account it was greatly prized in the early history of mankind, before the discovery of metals, for the manufacture of weapons and implements, as shown by its distribution in these forms and in unworked pieces over the world. It has long been greatly valued by the Chinese, who have devoted the most laborious work to fashioning it into objects for personal adornment and use. These objects, such as vases, bowls, etc., are often carved with wonderful skill and taste and are greatly prized for their artistic value. The rock is only known in place in upper Burma and in the Kuen-lun Mountains of Turkestan. Its origin is uncertain, but its chemical composition suggests that it may be a metamorphosed igneous rock of high soda content, such as nephelite syenite. A green hornblende rock called *nephrite*, from Siberia and New Zealand, has similar properties and uses and is frequently mistaken for jade.

Cipolin is a marble full of mica, which may show transitions to calcareous mica schist. Usually other minerals, sometimes in considerable variety, are also present.

Dolomite Marble, Magnesium Silicate Rocks. As mentioned under dolomite, the term dolomite used as a rock name does not necessarily imply that the substance composing the rock is pure dolomite, in the mineralogical sense. There is generally an excess of calcium carbonate present, so that the composition is a mixture of dolomite, $CaMg(CO_3)_2$, and calcite, $CaCO_3$. Just as marble is related to ordinary limestone, so is dolomite marble to ordinary dolomite rock. In a practical way no distinction can be drawn between the two varieties of marble, except chemically. See dolomite under the rock minerals. Like ordinary marble, dolomite marble is one end of a series of metamorphic rocks, which, beginning with a pure carbonate, becomes a mixture of carbonates and silicates, and ends in pure silicate rocks. The causes and processes are identical with those described under marble, but in this case the presence of magnesium causes the formation of silicate minerals in which this element is either the only metal, or a very important one. Thus in distinction from the calcium carbonate-silicate series, this may be called the magnesium carbonate-silicate series. The magnesium silicates thus produced in the zone of constructive metamorphism may be anhydrous, or nearly so; when the rocks rise, by erosion or otherwise, into the zone of hydration, they may be secondarily converted into serpentine, $H_4Mg_3Si_2O_9$, or sometimes into talc, $H_2Mg_3(SiO_3)_4$. Thus these rocks are in many places closely connected with the talc schists previously described, while their relation to serpentine is mentioned under that rock. The more important magnesium silicates taking part in the series are olivine, enstatite, chondrodite, diopside, tremolite, phlogopite, etc., and secondarily serpentine and talc, as stated above. Of the varied rocks formed by these mixtures, only a few of the most important can be mentioned.

Crystalline dolomites, or dolomitic marbles filled with variable mixtures of minerals, chondrodite, phlogopite, pyroxenes, etc., with others, such as magnetite, spinel, apatite, graphite, etc., derived from original impurities, are found rather commonly in the metamorphic areas in the eastern United States and Canada, but have received no distinctive names, as rocks. They appear to have been formed sometimes by contact, sometimes by regional metamorphism, often by a combination of both.

Ophicalcite is a mixture of white calcite and green serpentine, the latter often in veins, spots, or clouded through the rock. A part of the " verde antique " marble of the ancients, used for ornamental purposes, appears to have been a variety of ophicalcite. It occurs in Canada, northern New York, and various places in Europe.

Soapstone and talc schist. Part of the rocks included under these names belong in this series: they have already been described under a previous section. *Listwänite*, which occurs in the Ural Mountains and in Spain, is a mixture of magnesium carbonates (magnesite, $MgCO_3$, and dolomite), with talc, and with more or less quartz. *Sagvandite,* from Norway, is a granular mixture of varieties of magnesite and enstatite ($MgSiO_3$) containing ferrous iron.

Amphibolites. Many of the hornblende schists or amphibolites, previously described in a separate section, are the result of the transformation of impure limestones and dolomites into metamorphic rocks. This has already been discussed, but it should be again mentioned here, because the amphibolites, made in this way, form one of the most important members of the calcium and magnesium series of carbonate-silicate rocks described above.

Occurrence of Minerals and Ores. The crystalline marbles and dolomites, in addition to the minerals mentioned above, not infrequently, owing to local causes, contain a great variety of others. Thus at Franklin Furnace, New Jersey, owing to the presence of zinc and manganese, a number of minerals containing these metals have been produced, forming useful ores. Ore-bodies are mostly developed in these rocks, however, by contact metamorphism, but in some places the minerals developed by regional metamorphism are of such a character, and in such quantity, that they may be usefully exploited. Many of the famous mineral localities, specimens from which are commonly seen in collections, are in these rocks. The minerals thus found embedded as crystals in calcite and dolomite generally have the angles between the faces more or less rounded and are veined with calcite in their cracks.

Serpentine

General Properties. No close distinction between serpentine, as it has been described as a mineral, and serpentine as a rock can be made. As a mineral the chemically pure substance was considered, but serpentine as a rock is generally more or less impure from the presence of other minerals which are mixed with it. Serpentine rocks are generally compact, of a dull to waxy luster, and of a smooth to splintery fracture. If tolerably pure they are soft and can be cut by the knife, but they are sometimes saturated by deposited silica, which makes them much harder. The general color is green, characteristically a yellowish-green; but sometimes yellow, yellow-brown, reddish-brown, and dark green to black. On smooth surfaces the rock has a somewhat greasy feel, recalling talc schists, from which it is, however, readily distinguished by its superior hardness. Talc leaves its mark on cloth, while serpentine does not. The yellow-green color resembles also that of epidote rocks, but here the superior hardness of the epidote serves as a distinction.

Associated Minerals. Other minerals which may accompany the serpentine, and which may at times be seen in it, are remains of the magnesium silicates from which it has been formed, — olivine, pyroxene, and hornblende. Metallic-looking specks or crystals of ores are common, — magnetite, chromite, etc. In some varieties garnet occurs, chiefly pyrope, and the garnet used for gems comes in large part from a serpentine in Bohemia. Serpentine is the source of the platinum in the placers of the Ural Mountains, and of the nickel ores in New Caledonia and other places. Serpentine is generally accompanied by other secondary minerals, by chlorite (sometimes the purple-red variety kämmererite containing chromium), by talc, and by magnesium carbonates, magnesite, $MgCO_3$, and breunnerite, $Mg,FeCO_3$, etc. Serpentine rocks are usually massive but sometimes schistose (serpentine schist). Not infrequently they are seamed by veins of the finely fibrous variety of the mineral called chrysotile, which has the structure of asbestos and is often so called.

Chemical Composition. The chemical composition of serpentine rocks approaches that of the pure mineral, but generally differs somewhat on account of the other minerals present. This is seen in the appended analyses:

	SiO_2	Al_2O_3	Cr_2O_3	Fe_2O_3	FeO	NiO	MgO	CaO	H_2O	CO_2	XyO	Total
I...	40.4	1.9	0.3	2.8	4.3	0.5	36.0	0.7	10.7	1.4	0.6	99.6
II..	36.6	1.0	0.3	7.3	0.4	0.3	40.3	0.1	13.4	...	0.4	100.1
III.	38.6	1.3	0.5	5.6	2.2	0.1	39.1	0.9	11.3	0.5	0.2	100.3
IV .	36.9	1.4	...	6.9	4.0	...	36.0	1.4	13.1	...	...	99.7
V ..	42.3	0.8	...	...	2.6	...	40.3	1.3	12.5	...	0.5	100.3
VI .	44.1	...	...	...	...	...	43.0	...	12.9	...	...	100.0

I, Serpentine, dark-green, Rowe, Massachusetts; II, Serpentine, from pyroxenite dike, Mount Diablo, California; III, Serpentine, Iron Mountain, Oregon; IV, Serpentine, from hornblende schist, Vosges Mountains, Germany; V, Serpentine, white, selected pure mineral, Brewster, New York; VI, Theoretical composition of pure mineral, $H_4Mg_3Si_2O_9$.

The presence of small quantities of nickel and chromium oxides is a very common feature.

Origin. Serpentine rocks are secondary in nature, being formed when previously existent rocks consisting wholly or chiefly of magnesium silicates are exposed to the processes at work in the zone of hydration. Their origin may thus be twofold: they may be formed from igneous rocks, such as peridotite, dunite, etc.; or when amphibolites or hornblende schists, which have been made from sediments in the zone of constructive metamorphism, are brought by erosion into the zone of hydration, they may be converted into serpentines. Thus the origin of the material may be igneous or sedimentary, but, whereas the igneous rocks may pass directly into serpentine, the sedimentary ones must first pass through an intermediate metamorphic stage (hornblende schists, etc.), and may later be converted to serpentine. In this connection what has been said elsewhere on the alteration of peridotites and allied rocks should be read. No formula can be given for the determination of the origin of a serpentine; the geologic mode of occurrence and relation to other rock masses is often a help, while the presence of nickel and chromium, — substances to be expected in igneous, but not in sedimentary rocks, — if it can be shown, is very significant.

Occurrence. Serpentine is a common rock, and, while it rarely forms large masses or covers extensive areas, it is widely distributed over the world. In the form of layers, lenticular masses, etc., it is common in metamorphic regions from the alteration of both igneous and metamorphic rocks, and it thus occurs in eastern Canada, New England, New York, Pennsylvania, Maryland, California, Oregon, and other states; in southern England, Germany, the Alps, and various other places. It also occurs in non-metamorphic sedimentary areas, where it is due to the conversion of igneous rocks which have penetrated the strata, as in places in Quebec, New Brunswick, New York State, etc.

Alteration, Uses. Serpentine shows great resistance to the action of the weathering agencies at the Earth's surface, but eventually breaks down into a mixture of carbonates and silica, mixed with ferruginous matter. The soils thus formed, on account of the lack of alkalies and lime, are extremely barren, and often little or no vegetation grows upon them.

In Cuba, lateritization of serpentine has produced iron-ore deposits which in size are of the first magnitude.

On account of its beautiful coloring, serpentine has been largely quarried for use as an ornamental stone, being used for interior purposes much as highly colored marbles are. It is sometimes used for the same objects as soapstone but its softness constitutes an objection to its employment. In some places the seams of fibrous chrysotile which it contains are mined for use as asbestos. Its value as a source of ores of nickel, chromium, etc., has already been commented upon, and is further mentioned under peridotites and allied rocks.

Iron Oxide Rocks

Itabirite. This rock is composed chiefly of micaceous hematite and quartz. The micaceous hematite, or " specular iron ore " as it is often called, is in very thin tablets or leaves of irregular outline, while the quartz is in aggregates of grains. It much resembles mica schist, and if one were to imagine the mica of such a schist replaced by a substance of mica-like thinness but with the metallic luster of polished iron, one would have a good idea of the appearance of this rock. Micaceous hematite is indeed of not infrequent occurrence in genuine mica schists, and by its increase, transition forms to itabirite are produced. Also, just as the relative quantities of quartz and mica vary in different layers of mica schist, so do the micaceous hematite and quartz vary in itabirite; thus there are layers poor in quartz, and others quite rich in it, of very variable thickness. In addition to the mica, magnetite, pyrite, talc, garnet, and others may occur as perceptible accessory minerals. The rock is generally granular to fine granular; very schistose; of a dark color on the cross-fracture; and exhibits on the chief fracture the shining steel-like luster of the specular iron ore. Sometimes the amount of the iron mineral is so great as practically to conceal the quartz. Itabirite forms extensive areas in Brazil and on the Gold Coast of Africa. It also occurs in North and South Carolina, in Canada, Norway, Germany, etc. It has probably been formed by the metamorphism of sandstones and shales rich in deposited ferruginous matter, limonite, etc.

Jaspilite is a name given to banded rocks that consist of alternate layers of red chert and hematite. They occur in the older Pre-Cambrian iron formations of the Lake Superior region. They are metamorphosed ferruginous cherts. See page 306.

Magnetite Rock. This is a compact to granular aggregate of grains of magnetite, dark-colored to black, and heavy. The properties are those described under the mineral. Hematite is very commonly mixed with it, and a variety of other minerals, such as ilmenite, pyrite, quartz, calcite, garnet, etc., according to the mode of occurrence. The origin of magnetite rock is various; thus it may occur as masses included in, or associated with, igneous rocks, and is then regarded as a differentiated phase of such rocks, as mentioned under them. The associated minerals then vary with the kind of rock, as nephelite and augite when with nephelite syenite (Arkansas, Brazil, Sweden); olivine, pyroxene, calcic feldspar when with gabbros (Adirondacks, Sweden, Canada, Colorado, etc.). It is also found as a contact formation where igneous rocks have metamorphosed beds of limonite, siderite, etc. Finally it occurs in areas of regional metamorphism, in the form of layers and lenses in the midst of gneisses and schists, and often associated with metamorphosed limestones and dolomites. It then often contains calcite and dolomite, as well as the more common of the silicate minerals described as associates of marble, such as garnet, pyroxene, hornblende, etc. It is probably due to the metamorphism of beds of impure limonite, clay-ironstone, etc. Deposits of magnetite rock occur in many places in the United States and Canada, in Scandinavia, Germany, the Ural Mountains, etc., and are of great importance as sources of iron ore. Those that are differentiates of gabbro and anorthosite are, however, generally useless on account of the presence of ilmenite, which has so far prevented their being profitably smelted.

Emery. This is a granular rock of a dark gray to black color, consisting mainly of grains of gray or bluish corundum, often mixed with magnetite, and associated with other minerals. It is sometimes quite schistose. It is easily recognized by its weight and excessive hardness (corundum = 9). It occurs, as layers of relatively small volume in the crystalline schists, in Asia Minor, the Island of Naxos, Germany, Massachusetts, etc. Its use as an abrasive material, on account of the corundum it contains, is well known.

CHAPTER XII

THE DETERMINATION OF ROCKS

The amount of difficulty encountered in the determination and classification of rocks depends on the degree of refinement sought and the means at command for attaining it. It is obvious that the fine distinctions made by petrographers among rocks, especially among the igneous ones, cannot be carried into ordinary practice, unless the petrographer's methods — the use of the microscope and chemical analyses — are employed. This, of course, cannot ordinarily be done, and we are thus limited to the means of observation which have been used in this book, and to simple classifications and the limited number of rock names that these classifications afford. This fact has already been commented upon in discussing the classification of the igneous rocks, and need not be repeated.

Rock Characters used in Determination. The characters of rocks that may be used for their megascopic determination are of two kinds, *mineral* and *general.* If the rock is composed wholly or in part of mineral grains that are large enough to be distinctly seen with the eye or lens and that may be, if necessary, handled and tested, then the determination may proceed by a study of the minerals, their kinds, relative abundance, and relation to each other (rock-texture); these are the mineral characters. In this procedure there is no essential difference between the microscopic and megascopic study of rocks; one can accomplish, in the main, by examining the fractured surface of a coarse rock, what can be done with the microscope on the thin section of any rock. The individual minerals may be studied and tested according to the methods given in Chapter V; if in the field, the simple test of Table No. I may be used; if the conveniences of a laboratory are at hand, the more complete table, No. II, can be employed. If it has already been determined, perhaps in the field, whether the rock is igneous, sedimentary, or metamorphic, its place can usually be very quickly settled. Even if all the different kinds of minerals cannot be told, the determination of one or more will generally be of service.

The *general* characters are those resulting from the combination of mineral grains; they might be termed composite features of rocks. They include *color*, *structure*,* *texture*, *fracture*, *hardness*, and *specific gravity*. Of these the specific gravity is of the least general applicability, because a special apparatus is required to determine it. The reaction of the rock with acids is also at times extremely useful as a test, and may be added to the list. These general characters are so useful that they deserve some separate mention in regard to their employment in rock determination.

Color. The rock color is the general resultant of the colors of the combined mineral grains. Certain general conclusions may be drawn from the color of a rock; thus if it is pure white or nearly so, it is certain that compounds of iron are either wanting in it, or are only present in traces, and in general the rock is either a sandstone, quartzite, marble, gypsum, or a nearly feldspathic igneous rock, such as anorthosite, aplite, syenite, or felsite. Red, brown, and green colors indicate the presence of iron compounds; black or stone gray may also indicate this, but in a sedimentary rock these colors may result from carbonaceous material.

Structure. If the rock has a pronounced structure, it may be of great assistance in determining the general class to which it belongs, especially if the geological relations of the rock mass cannot be determined. Thus if a rock mass possesses a pronounced columnar, a highly vesicular, or an amygdaloidal structure, it is almost certainly of igneous origin; if a laminated or banded structure, it is probably sedimentary; but banding

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* The difference between the use of "structure" and "texture" has been already explained, p. 159.

cannot be unreservedly relied on, because igneous rocks, especially lavas, may assume a banded structure by flowage, while metamorphic rocks may acquire it by shearing movement. The oölitic structure indicates a sedimentary rock. In general, structure must be considered in connection with texture and other properties.

Texture. Certain textures are of definite assistance in determining the family to which a rock belongs. Thus the glassy texture is definite proof that the rock is of igneous origin; a porphyritic texture shows the same thing, especially if the phenocrysts are well crystallized, and of quartz, or feldspar, or both. Metamorphic rocks also contain, at times, prominent well-formed crystals set in a finer matrix, which are similar to phenocrysts, as, for instance, garnet and staurolite, but in general these rocks also possess at the same time a well-foliated structure, which helps to distinguish them. Sedimentary rocks do not exhibit this texture. The mere contrast in color of a few dark mineral grains among many lighter ones must not be mistaken for a porphyritic texture. In general, a hard, firm, highly crystalline texture, alike in appearances in all directions through the rock, is indicative of an igneous origin; but there are many exceptions to this rule, as shown in various marbles and quartzites. If a rock has a highly crystalline texture, and at the same time a foliated structure, it is probably metamorphic.

Hardness. This character, which can readily be tested in a rough way in the field, is very useful in distinguishing between certain classes of rocks. Thus very fine-grained compact sandstones (or quartzites), limestones, and aphanitic igneous rocks often look much alike in specimens, but a simple test of hardness with the knife-point will at once distinguish between the limestones (carbonate rocks, soft) and the others mentioned (silicate, or silica rocks, hard). If the rock is not very firm, care must be taken not to confuse the mere breaking down or crushing of the rock fabric with actual scratching of its component minerals. If the rock itself is used to scratch with, care must also be taken to test a number of corners, or edges, so that some single grain, harder than the average, may not produce a false impression of the average hardness.

Fracture. This is of less importance than the foregoing characters, but yet in some ways is of value. Most rocks that are firm and solid enough to have a distinct fracture exhibit a more or less rough, hackly one. Those that are fine-grained or aphanitic, and contain a large amount of silica or are wholly composed of it, such as felsites, quartzites, flint, etc., possess a more or less distinct conchoidal fracture, and the surface may be splintery. Some fine-grained limestones also have a splintery fracture, and may even approach the conchoidal. Natural glasses, such as obsidian, have a beautiful conchoidal fracture.

Specific Gravity. This property is of much greater value in the determination of minerals than in that of rocks. It cannot, of course, be used in the field, as definite apparatus is required to determine it, as described in Chapter III, under minerals; nevertheless, even in the field, a rough distinction may be made between light and heavy rocks, by weighing them in the hand. Rocks that are dark-colored and very heavy, in general, are composed largely, or chiefly, of iron-bearing minerals, and are likely to be of igneous or of metamorphic origin.

Treatment with Acid. This is particularly useful in distinguishing the carbonate from the silicate rocks. The method of treatment has been fully described in Chapter V, and need not be repeated here. If necessary almost any acid may be used, such as vinegar (acetic acid), or lemon juice. For field use a few powdered crystals of citric acid may be conveniently carried, and dissolved, when needed, in a little water; the test for effervescence can thus be readily made. The test for gelatinization, as described in Chapter V, is also very useful in distinguishing the nephelite syenites from other syenites and from granites, and also in separating the effusive representative of the group, the phonolite variety, from the other felsites. It should be remembered that olivine, which, however, chiefly occurs in the dark ferromagnesian rocks, gabbros, peridotites, and basalts, also gives this gelatinization test.

Determination in the Field. The best method of determining the family to which a rock belongs, that is, whether it is sedimentary, igneous, or metamorphic, is to study its characters in the place in which it occurs, and its relation to other rock masses. These features, and the larger ones of its structure, may be very apparent in the field, while a simple hand specimen may entirely fail to show them. The structure of a granite gneiss, for instance, may be very clear on the surface of a field exposure, and be quite inappreciable in a small specimen. It is not necessary to give here the characters and relations by which the class may be determined; this is a geological rather than a petrographical problem, and has been sufficiently commented upon in Chapters VI, VIII, and X. If the family has been determined in the field, and the rock is coarse-textured, so that the mineral grains can be seen, and if necessary handled, Table I (p. 120) of Chapter V may be used for their identification; and by then referring to the classification of the appropriate family, the place of the rock in general can be readily determined.

Table for Rock Determination. Appended to this chapter is a table which may be used for the determination of the more important kinds of rocks. It is based essentially on the one given by Geikie, in his "Textbook of Geology," which has, however, been considerably modified, and extended to meet the needs of this work. As the tests which it demands are very simple, consisting for the most part of those relating to hardness and effervescence with acid, it may be readily used, even in the field. It must be remembered, however, that a table of this nature can be only quite general in character, and applicable to rocks of well-defined types. The kinds of rock grade into one another in so many ways, as has been described in a number of places in this work, that not only the student, but even the experienced geologist, will sometimes be puzzled as to the proper designation a particular specimen should receive. If this fact is borne in mind, however, it is believed that the table will prove useful in aiding one to classify the common rocks.

TABLE FOR DETERMINING THE COMMON ROCKS

The newly fractured surface of the unweathered rock shows one of the following features:

A. It is wholly or partly glassy. See **A** below for subdivisions.

B. Not glassy; of a dull or stony appearance; homogeneous; without particular texture, or so fine-grained that the individual grains cannot be seen or recognized. See **B.**

C. Distinctly grained and crystalline; the grains can be seen and determined. See **C.**

D. Has a distinctly foliated or gneissic structure. See **D.**

E. Has a clearly fragmental composition. See **E.**

A. *Wholly or partly glassy.* [illegible]

1. Wholly of glass; solid; strong vitreous luster. *Obsidian,* p. 266.

2. Wholly of glass; solid; resinous or dull pitchy luster. *Pitchstone,* p. 270. (Obsidian and pitchstone may contain spherulites.)

3. Wholly of glass, but cellular or froth-like. *Pumice,* p. 272.

4. Of glass, but enamel-like, and composed of small, concentric spheroids. *Perlite,* p. 270.

5. Partly of glass and partly of distinct, embedded crystals. *Vitrophyre,* p. 273.

(The above forms are generally associated with, or pass into, felsite lavas.)

6. Glass associated with or passing into basalt; rare. *Tachylite,* p. 275.

B. *Compact, close-grained, and dull or stony; not glassy.*

a. Very soft; can be scratched with the finger-nail.

1. Has a strong earthy or clay odor when breathed upon; rubbed strongly between the fingers, has ultimately a smooth, greasy feeling; does not effervesce with acids. Various colors. *Clay,* p. 341.

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TABLE FOR DETERMINING THE COMMON ROCKS

Continued

2. Friable; crumbling; soils the fingers; little or no clay odor; lively effervescence with acids; color white or light yellowish, etc. *Chalk*, p. 319, or perhaps *marl*, p. 324. (Marl may give a distinct clay odor.) S

3. General characters as in 2, but does not effervesce with acids. *Diatomaceous earth*, p. 307.

4. Harder, more compact than 1, 2, and 3. No clay odor; does not effervesce; composed of a mineral with a good cleavage; sometimes fibrous; occurs in beds or veins. *Gypsum*, p. 302. S

5. White to green, or gray; does not effervesce; no clay odor; mass has a soft, greasy feel; is often foliated or shows a micaceous cleavage; folia inelastic; marks cloth. *Talc rock*, p. 389. M

b. Not scratched by the nail, but easily scratched or cut with the knife.

1. Composed of excessively fine, almost imperceptible particles; dull, even appearance; gives clay odor when breathed on; feeble effervescence or none; has a laminated or stratified structure and usually breaks easily into chippy flakes; generally gray, but often red, yellow, brown, bluish, or black. *Shale*, p. 341. S

2. Clay odor absent or feeble; brisk effervescence with acid; white streak; commonly gray; sometimes white to brown or black. *Limestone*, p. 313. S

3. As in 2, but feeble effervescence in acid, which becomes brisk when rock is powdered or when the acid is heated; generally white, yellowish, or pale brown. *Dolomite*, p. 316. S

4. Pale to dark green or black, sometimes reddish; soapy or greasy feel; translucent on thin edges; waxy or oily appearing; subconchoidal or splintery fracture; no effervescence. *Serpentine*, p. 405. M

c. Not scratched or cut with the knife; scratches glass; does not effervesce with acid.

1. Various colors, white to red or purple, brown to dark gray; often gives a clay odor; frequently shows banded flow structure. *Felsite*, p. 253.

2. Very hard; any corner or angle scratches feldspar; no clay odor; scratches steel readily; light colors to brown or black; pronounced conchoidal fracture; glimmering horny appearance. A siliceous rock; either *flint*, p. 305, or perhaps the rhyolite variety of *felsite*, p. 254.

TABLE FOR DETERMINING THE COMMON ROCKS
Continued

3. Not so hard as 1 and 2. Does not scratch feldspar; color black, very dark gray or green; is heavy; sometimes shows a cellular or slaggy structure; sometimes contains amygdules. *Basalt*, p. 257.

C. *Distinctly grained and crystalline; grains wholly or partly determinable.*

a. Is easily scratched with the knife.

1. Effervesces briskly with cold acid. *Limestone*, p. 313, or more probably *limestone marble*, p. 398.
2. Effervesces with cold acid only when the powdered rock is treated. *Dolomite marble*, p. 403.
3. Does not effervesce with acid; probably granular crystalline. *Gypsum*, p. 302, or *anhydrite*, p. 303.
4. Soluble, with distinct saline taste. *Rock salt*, p. 304.

b. Hard; cannot be scratched with the knife, or scratches with difficulty. Silicate rocks, two cases arise, I and II.

I. It is composed of grains of approximately equal size; i.e., it is *even-granular*, like common granite. See **I** for subdivisions.

II. It is composed of larger, distinct crystals embedded in a finer-grained groundmass; i.e., it is a *porphyry*. See **II** for subdivisions.

I. *An even-granular, massive, silicate rock.* See p. 155.

1. Mainly or wholly composed of quartz and feldspar. *Granite*, p. 207. See also *aplite*, p. 219.
2. Mainly or wholly composed of feldspar without quartz. *Syenite*, p. 225. See also *nephelite syenite*, p. 227, and *anorthosite*, p. 239.
3. Composed of feldspar and a dark ferromagnesian mineral; the latter is less than or equals the feldspar: *Diorite*, p. 230. The dark mineral equals or exceeds the feldspar. *Gabbro*, p. 233.
4. Composed entirely, or almost entirely, of ferromagnesian minerals; generally heavy and dark green to black (sometimes yellowish, *dunite*). *Peridotite, pyroxenite*, etc., see p. 243.
5. Composed of grains of quartz; scratches glass or feldspar readily. *Sandstone*, p. 336, or *quartzite*, p. 381.

TABLE FOR DETERMINING THE COMMON ROCKS

Continued

6. Much less commonly than the above, massive silicate rocks produced by metamorphism may occur in this division. There are a number of different varieties, depending on the particular mineral, or minerals. *Epidote rock*, *garnet rock*, etc., would be examples. See *contact metamorphism*, pp. 184, 189, and *carbonate-silicate* rocks, p. 398.

II. *A porphyry* (see p. 153), *composed of phenocrysts and a groundmass.*

1. Phenocrysts of quartz and feldspar and, perhaps, of a ferromagnesian mineral in a groundmass of the same. *Granite porphyry*, p. 248.
2. Phenocrysts of orthoclase (and often of a ferromagnesian mineral) in groundmass of predominant feldspar. *Syenite porphyry*, p. 250.
3. Phenocrysts of ferromagnesian minerals, or feldspar, or both, in a groundmass of feldspar and ferromagnesian minerals; feldspar phenocrysts frequently striated. *Diorite porphyry*, p. 250.
4. Phenocrysts of quartz, or feldspar, or both, and sometimes of ferromagnesian minerals, in a predominant groundmass of light color and aphanitic aspect. *Felsite porphyry*, p. 255.
5. Phenocrysts of feldspar, or of a ferromagnesian mineral, or both, in an aphanitic, dark to black, and heavy groundmass. *Basalt porphyry*, p. 257.

D. *Has a distinctly foliated, gneissic, or slaty structure.*

1. Coarse-grained and roughly foliated. *Gneiss*, p. 365.
2. Consists mainly or largely of mica; often considerable quartz is present. Frequently contains crystals of dark red to black garnet, more rarely staurolite, cyanite, etc. *Mica schist*, p. 376.
3. Medium green, dark green or black; consists mostly of a felted or matted mass of small, to very fine or microscopic, bladed, or needle-like crystals arranged mostly in one general direction, which promotes the schistose cleavage. Other minerals, such as garnet, may be present. *Hornblende schist* or *amphibolite* (p. 393).
4. Extremely fine-grained and fissile, splitting easily into thin, more or less tough, ringing slabs; usually dark gray, or green to black, but sometimes showing other colors. *Slate*, p. 384.
5. Very fissile, but soft to the feel; laminæ not tough, but often brittle or crumbling; pronounced silky luster on the cleavage face. *Phyllite*, p. 387. (Some contain large crystals of staurolite, garnet, biotite, etc.)

TABLE FOR DETERMINING THE COMMON ROCKS
Continued

6. Soft, greasy feel; marks cloth; easily scratched with the fingernail; usually whitish to light gray, or green. *Talc schist,* p. 389.

7. Smooth feel; soft; green to dark green; glimmering luster. *Chlorite schist,* p. 390.

E. *Has a clearly fragmental composition; is seen to be composed of fragments or pebbles of other rocks, or of smaller angular or rounded mineral fragments; if the latter, frequently shows evidences of stratification.*

1. The pebbles range from the size of a pea up and are rounded; quartz ones are common; they are embedded in more or less of a cement. *Conglomerate,* p. 333.

2. The pebbles are angular in shape. *Breccia,* p. 333.

3. Composed of various-sized angular fragments of volcanic rocks, such as felsite and felsite porphyry, of bits of pumice, or cellular lava, or of rounded, vesicular, volcanic bombs, etc., mixed with fine compacted material (volcanic ash). *Volcanic tuff* and *breccia,* p. 279.

4. Composed of more or less angular, but sometimes rounded grains, in size from that of a pea down; the grains are mostly, or wholly, composed of quartz, and scratch feldspar. Generally some cement is present, which, if the rock is light colored, tends to effervesce with acid (calcium carbonate); if red or brown, does not. *Sandstone,* p. 336.

5. As in 4 but feldspar predominates over the quartz grains, thus simulating a granite in appearance. *Arkose,* p. 340.

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(Rock names are printed in italics.)

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Look up phillites in Lab.
(mica). Slate to mica schist.